

*Appendix E –
Hood Canal Floating Bridge Report
(3/20/2014 Revision)*

HOOD CANAL FLOATING BRIDGE

High Strength Anchor Bolts
Example of Application of Greased and
Sheathed Double Corrosion Protection Systems

DRAFT



For:
San Francisco-Oakland Bay Bridge
SAS pier E2 Anchor Bolts Study
By the Bay Area Management
Consultants (BAMC) For the Bay Area
Toll Authority (BATA)

March 20, 2014

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Report Background:

Bay Area Management Consultants (BAMC):

BAMC is a Joint Venture of URS Corporation and Hatch Mott MacDonald (HMM) Corporation. BAMC was retained by BATA (Bay Area Toll Authority) to provide Program Management Oversight Services for the State of California's Toll Bridge Seismic Retrofit Program. BAMC was selected through a public competitively based RFP process in 2005 pursuant to services required by the 2005 California law AB144. In the performance of those services BAMC was requested by BATA to study bridges having large diameter ASTM A354 BD galvanized bolts having a high pre-tension application of $0.7F_u$, similar to those utilized on the new San Francisco Oakland Bay Bridge East Span SAS structure.

In that search assignment BAMC found only one bridge having 3" diameter galvanized rods with a pre-tension design load requirement of $0.7F_u$. That bridge is the Hood Canal Floating Bridge in Washington State.

The following report is an analysis of the records of the design and construction of the Hood Canal Floating Bridge and specifically the application of high strength anchor rods comparable to the SAS E2 anchor rods.

The Author of the report is Robert Shulock of Bainbridge Structures Group LLC a sub-consultant to BAMC.

Contributors to the report include:

Ted S Hall - Hatch Mott MacDonald Corporation
DR. Jeff Gorman- Dominion Engineering, Inc.
Mazen Wahbeh – Alta Vista Solutions
Alan Cavendish-Tribe - Mott MacDonald Limited
Ed Zhou- URS Corporation
Steven Christoffersen - URS Corporation
Michael J. Abrahams – Parsons Brinkerhoff
Geoff Swett – Washington Department of Transportation
Paul Knaebel - Washington Department of Transportation
Jay Dwight – Dwight CO LLC
Mark Lisin- Lisin Metallurgical Services
Melissa Pedersen- Hatch Mott MacDonald

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HS Anchor Bolts

Hood Canal Floating Bridge, Washington

I. Introduction

The **Hood Canal Floating Bridge** in the State of Washington carries SR 104 across Hood Canal, connecting the Olympic and Kitsap Peninsulas. Since its opening in 1961 it has become a vital link for residential, commercial and recreational travelers.



With a floating portion 6,530 feet long, the Hood Canal Bridge (HCB) is the world's longest floating bridge located in a saltwater tidal basin and the third longest floating bridge in the world. As the only crossing of the Hood Canal, the bridge is a vital component of the highway network in the North Puget Sound region, with an average daily traffic of 20,000 vehicles.

The HCB is composed of two prestressed concrete girder (PSG) approach spans, two Warren truss transition spans, twenty-nine post tensioned concrete floating pontoons, a PSG elevated roadway over the pontoons, forty-two submerged concrete anchors and near the center of the canal - two 300-foot concrete floating pontoon draw spans. The draw spans provide a navigation channel primarily for U.S. Navy ships and submarines passing to and from Bangor Naval Base.

The bridge crosses over a 1.5 mile wide and 340-foot-deep section of the Hood Canal that has a tidal variation of than 16 ½ feet. This fjord-like arm of Puget Sound is subject to frequent storms off the Pacific Ocean that generate fierce winds and accompanying large waves.

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Hood Canal Floating Bridge, Washington State

On February 13, 1979, the West Half of the HCB sank to the bottom of the Hood Canal during a major windstorm with sustained winds of 85 mph and gusts to 120 mph. The loss of this critical link from Seattle to the Olympic Peninsula resulted in a 100-mile detour and the activation of costly emergency ferry service.



Hood Canal Bridge – West Half Under Water, February 13, 1979

Contributing factors to the sinking of the West Half included severely corroded post tensioning wires, many of which had fractured previous to the storm and some that may have been compromised enough to have fractured during the storm, corrosion of the steel hatches at the top of every pontoon compartment that led to them being left open at the time of the storm,

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and missing bulk head seals at all of the bulkheads where the post tensioning cables passed between compartments - which negated the purpose of the bulkheaded compartments and allowed water that entered through the hatches to migrate the length of the bridge.

1.a. West Half Replacement

The design of the West Half replacement was awarded to the joint venture of Parsons Brinckerhoff and Raymond Technical Facilities, (PB/RT JV). The design and replacement of the West Half was completed in 1982. As part of the West Half design work, plans were prepared by PB/RT JV to replace the East Half, but due to funding constraints and the fact that the East Half is somewhat more sheltered from wave action, the East Half was rehabilitated and strengthened but the East Half replacement was not immediately constructed.

1.b. East Half Replacement

In 1998, the Washington Department of Transportation (WSDOT) decided to replace the East Half based on the 1982 plans, and to rehabilitate the West Half. When the design update began in 1998, it was initially anticipated that minimal changes would be required, and that the effort would focus on revising the plans and specifications to bring the East and West Half machinery, power and controls up to current codes and standards. However, due to advances in bridge technology, changes in available equipment and materials and lessons learned since the replacement of the West Half, a number of modifications were introduced, including significant modifications to both the East and West Half designs. In the words of Michael Abrahams, the PB/RT JV Engineer of Record, “...this provided ...a rare opportunity when one can design a structure, try it out for 20 years, and then have the opportunity to revisit the design.” One major change was that traffic in the region had increased and a wider deck was desired. This was a challenge as the increased width meant an increased dead load on the pontoons.

Adding to design complexity, all construction materials were required to withstand a highly corrosive marine environment. Despite the use of the weathering steel and the extensive application of galvanizing in the 1982 design, corrosion was a persistent problem in the aggressively corrosive marine environment. The primary changes were in the concrete specifications and design changes that dealt with the increased use of corrosion resistant steels and application of steel coatings – including galvanizing and painting of most all of the structural steel.

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The Hood Canal Floating Bridge Spans Alone Over Saltwater

The 1.5-mile-long floating bridge is built to withstand high winds and waves, strong current, large tidal variations and a severely corrosive environment.

There was much written concerning design changes that were implemented, but no written record was found that discussed design changes to the draw span A354 BD high strength anchor bolts. However, in discussions with Michael Abrahams, the Engineer of Record for both the East Half and West Half, he indicated that the performance of the A354 BD high strength anchor bolts was reviewed - and given the superior performance of the West Half design, i.e. black non-galvanized bolts in a greased duct - it was decided not to make any design changes to these bolts. Mr. Abrahams stated that the design of black HS anchor bolts in grease filled ducts was based on the nuclear power industry research and their practice for anchoring reactor enclosures - the use of grease filled ducts for both corrosion protection and to allow replacement of the post tensioned anchoring tendons.

The design was completed in early 2003 and the East Half Replacement and West Half Rehabilitation were advertised in the spring of 2003. In July, 2003, a contract was awarded to Kiewit - General to replace the East-Half and rehabilitate the West Half. The East Half replacement was completed and the bridge opened to traffic in June of 2009. The rehabilitation of the West Half was completed in early 2010.

An overview of the Bridge history, its design, re-design and replacements, can accessed at:

- http://www.youtube.com/watch?feature=player_detailpage&v=gLfNvZRIYpU
- <http://www.wsdot.wa.gov/Projects/SR104HoodCanalBridgeEast/Progress/drawspan.htm>

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1.c. High Strength Anchor Bolts

The HCB incorporates many different applications, corrosion protection systems and types high strength anchor bolts. HS anchor bolts of interest include those at the Steel A-Frame supporting the transition spans, the bolts holding the centering pyramid for the draw span and the bolts that anchor the supports for the draw span guide rollers.

Of particular interest are the large diameter **A354 BD bolts** that anchor the box beams which support the draw span guide rollers. The HCB is a working laboratory with respect to the use of these bolts - in corrosive environments, with the use various corrosion protection systems, and with high and varied pretensions. The bolts at both the West Half and East Half draw spans are of four inch and three inch diameter and ~20 foot long, have both exposed portions and greased and sheathed portions and were painted with the WSDOT three coat system. The West Half bolts have been in service for 31 years, are black (not galvanized) with the 4 inch bolts respectively pretensioned to 0.52 Fu and 0.78 Fu. The alloy is not known. The East Half bolts have been in service for over 4 ½ years, are galvanized, the 4 inch bolts and 3 inch bolts are respectively pretensioned to 0.52 Fu and 0.70 Fu, the 4 inch bolts are AISI 4140 alloy and the 3 inch bolts are of both AISI 4140 and 4340 alloys.

There have been no problems to date with the black bolts at the West Half. However, during construction of the East Half all 12 of the three inch diameter A354 BD bolts failed. Six of these failures were complete fractures caused by Hydrogen Embrittlement (HE) and six were deemed not acceptable for reuse due to visual indication of inelastic deformation.

1.d. Bay Area Management Consultant HCB Study

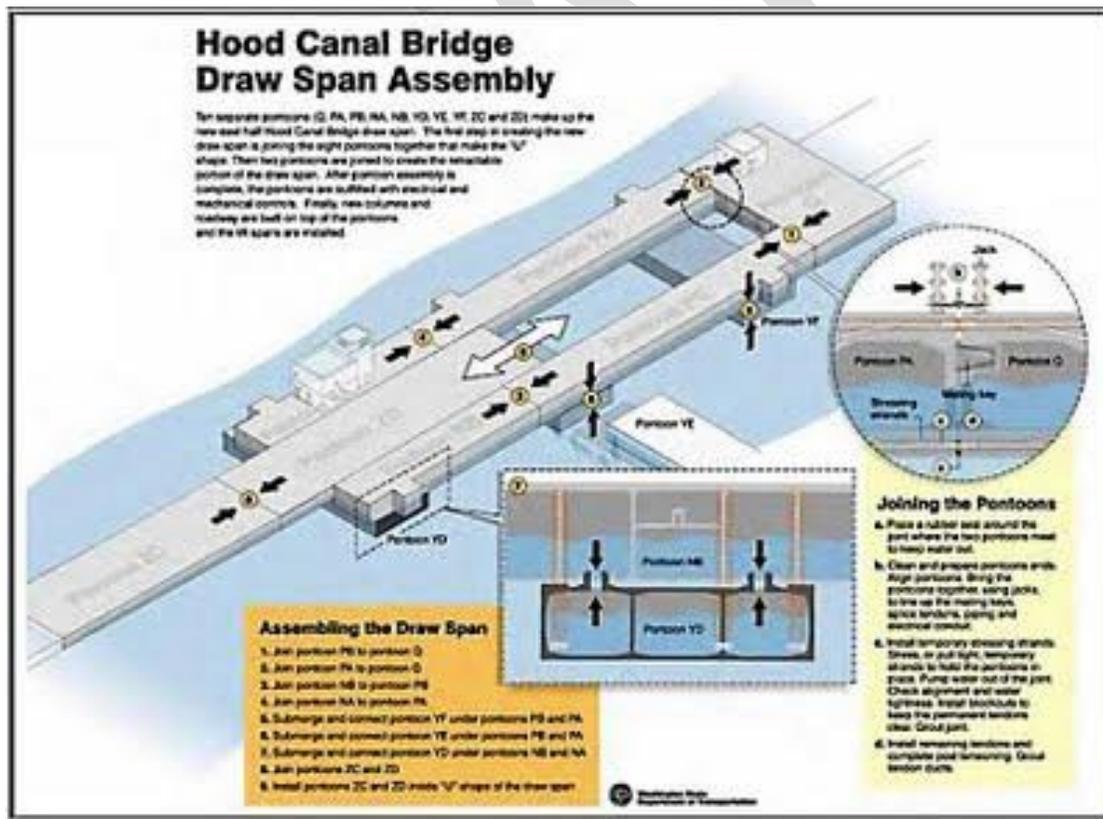
Given the similarities between the HCB A354 BD bolts and those used on the new San Francisco Oakland Bay Bridge (SFOBB), it was felt that a study of the lessons learned about the design, construction and performance of the HCB A354 BD bolts would provide information useful in evaluating the causes and possible remedies of the failures experienced with 2008 anchor rods. There was interest in both the black bolts installed on the West Half in 1982 and the galvanized bolts installed on the East Half in 2009. This report details the information and knowledge that was gained from the study. Reports of visits of Bay Area Management Consultants (BAMC) and Caltrans staff to the HCB are contained in the Appendix to this Report.



II. Draw Span – Guide Roller High Strength Anchor Bolts

Near the center of the Hood Canal Bridge there are two 300 foot floating draw spans that can be retracted to allow ship passage or to relieve wind and wave pressure on the bridge during storm events. Each draw span assembly includes a floating draw span - a U-shaped pontoon structure that provides an open well into which the draw span can be retracted. To retract the draw span, the 300-foot-long steel deck is lifted hydraulically to create an open well into which the draw span is retracted beneath the elevated deck into the cradle between the pontoon “forks”. After the draw span is extended back into the channel, the deck is hydraulically lowered to roadway level. The draw span is operated by a rack and pinion mechanism with twin 432-foot-long rack gears. Both spans are electronically controlled from a single control house.

When the draw span is extended into the channel and subject to direct wind/wave /surge action there are large dynamic loads on the guide rollers and subsequently large dynamic loads on the anchor bolts. *Forces on the bolts are highest from the hydrodynamic wind/wave loadings experienced during storm events that necessitate that the draw span be retracted to relieve pressure on the bridge.*



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Steel Deck at East Half Hydraulically Lifted

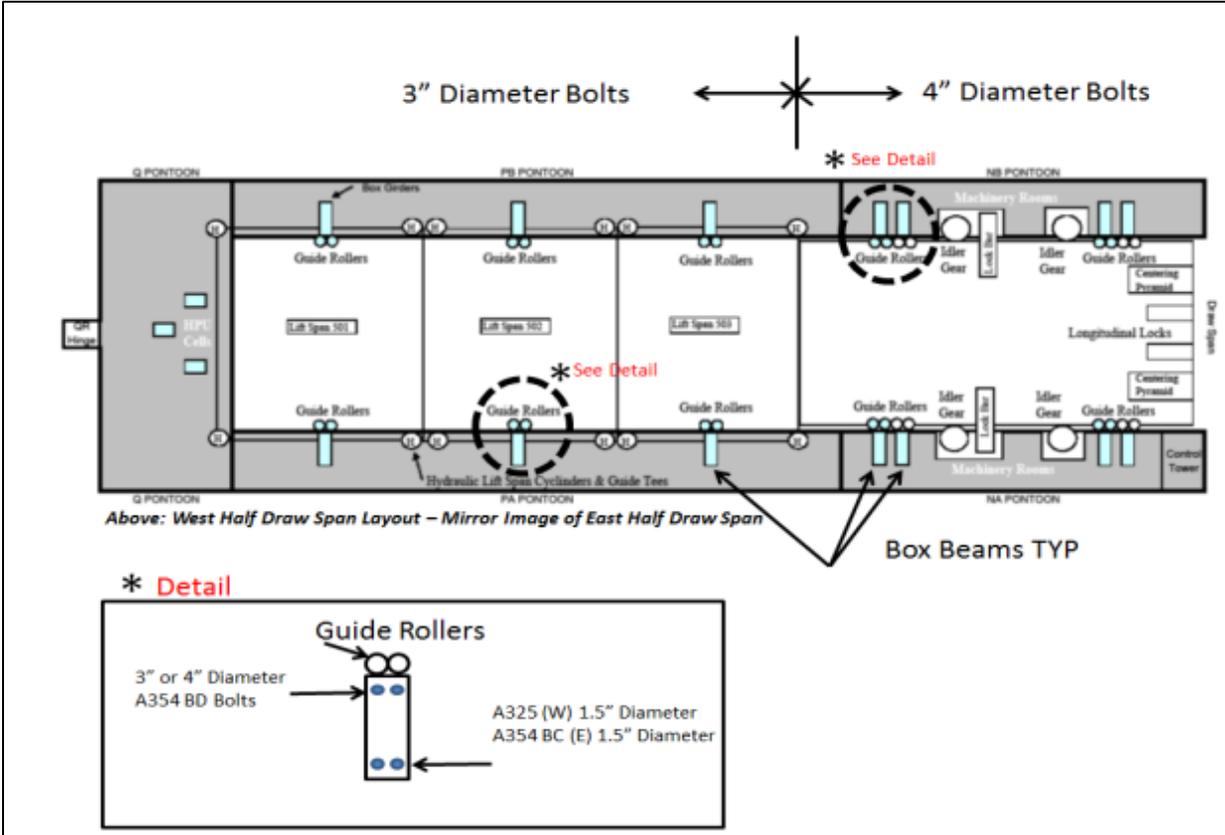
To see the draw span and guide roller operations go to:

- www.vimeo.com/4975186
- www.wsdot.wa.gov/Projects/SR104HoodCanalBridgeEast/Progress/drawspan.htm

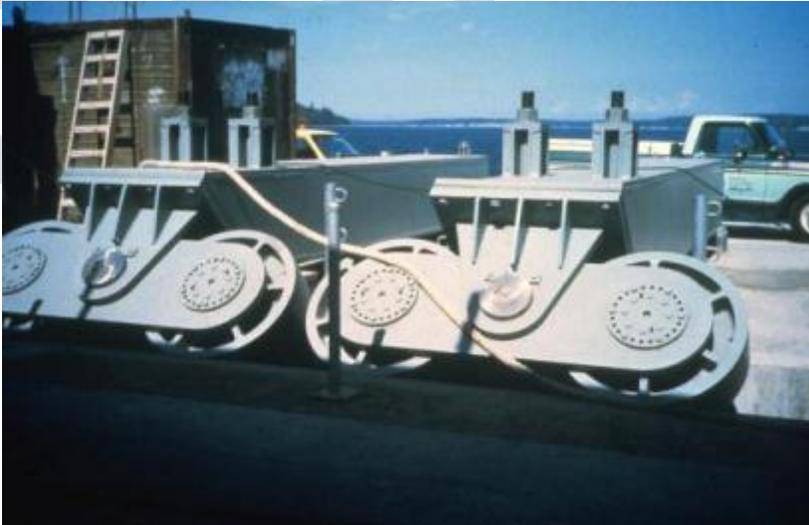
The draw span is secured and guided by a series of upper and lower guide rollers on each side of the draw span. The upper guide rollers are secured to a steel box beam that is connected to the fork pontoon with greased and sheathed HS anchor bolts. These rollers and their HS anchor bolts take horizontal shear and large upward vertical forces.

The guide rollers at the front of the pontoon fork take the majority of the force when the draw pontoon is extended and thus are more highly loaded than the rollers at the back portion of the pontoon fork. The upper guide roller layout is shown below. Note at the front portion of the fork there are 8 guide rollers - each with two 4 inch diameter, 20 foot long A354 BD bolts - and at the back portion of the fork there are 6 guide rollers - each with two 3 inch diameter, 20 foot long A354 BD bolts.

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Draw Span Upper Guide Roller Layout



Upper Guide Rollers and Box Beams with 4 inch Diameter A354 BD Anchor Bolts

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At the West Half the bolts are black, not galvanized ASTM A354 BD (Alloy unknown). At the East Half, the bolts are galvanized ASTM A354 BD bolts with the 16- 4 inch diameter bolts of AISI 4140 alloy and 12- 3 inch diameter bolts, 6 bolts of AISI 4340 alloy and 6 bolts of AISI 4140 alloy. The top and bottom portions of the bolts and nuts that are exposed and not in the greased ducts are painted with the WSDOT 3 coat system.

The anchor bolts farthest from the rollers at the back of the box beam are greased and sheathed, 1 ½ inch diameter, 6 ft. long. At the West Half the 1 ½ inch anchor bolts are black, not galvanized A325 bolts. At the East Half the 1 ½ inch anchor bolts are galvanized A354 BC bolts.

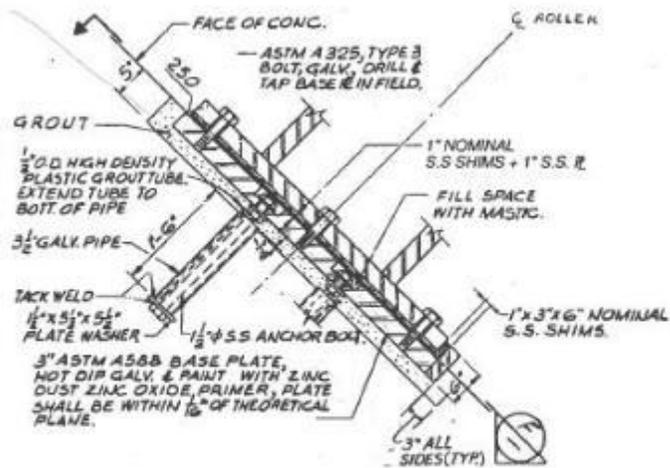


Upper and Lower Guide Rollers. Steel Box Beam with 3 inch Anchor Bolts nearest Rollers

The upper and lower guide rollers (in the picture above) keep the draw span pontoons on course when the draw span is being retracted or extended. The box beam that supports the upper guide rollers is shown with the ASTM A354 BD bolts visible behind the rollers.

The bolts that anchor the support of the lower draw span guide rollers are 1 ½ inch diameter, 2 ft. long, stainless steel A593 Type 316. They are in grout filled stainless steel ducts. These bolts are identical at the West and East halves.

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DETAIL 3
MS015

2003 Design Plans: Anchor Bolt detail for lower Guide Rollers (1981 similar)



West Half Guide Roller Replacement

III. West Half Replacement (1982) and Retrofit (2009)

The greased and sheathed 3 inch and 4 inch diameter anchor bolts securing the upper guide roller box beam in the West Half Replacement were black, not galvanized A354 BD bolts and the 1 ½ inch diameter anchor bolts were black, not galvanized A325 bolts. The threads were specified to be rolled after heat treatment. After stressing and then painting the exposed portions of the bolt and the nuts with the standard WSDOT three coat paint system, the sheathed portions of the bolts were injected with grease. They are shown as such in the 1981 Design Plans, Specifications and Shop Drawings, and have been verified as such by field inspection.

Design Plan Sheet M 216 Section B from 1981 shows the 4 inch bolts were to be tensioned to 870 kips or 0.53Fu, the 3 inch bolts to 713K or 0.78Fu and the 1 ½ inch bolts to be snug tight. Note: The MTR's and most all other as built information was discarded from WSDOT archives sometime before 2008, and as such is not available.

During the East Half Replacement in 2009 the West Half was renovated, including replacement of the guide rollers. At that time the anchor bolts were inspected, found to be in very good condition, and were not replaced. They are visually and ultrasonically inspected each year. The following pictures are from the BAMC visit to the HCB on June 28, 2013.



Bottom End of 4 inch Ungalvanized A354 BD Bolt

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Top End 4 inch Ungalvanized A354 BD, West Half, South Side

IV. East Half Replacement – 2009

The 2003 East Half Design Plans and Specifications, which were nearly identical to that of the 1981 West Half, indicate that the 3 inch and 4 inch diameter A354 BD anchor bolts were not to be galvanized. However, the 2007 Shop Drawing indicates that the A354 BD bolts were to be galvanized and recent visual inspections show these bolts to be galvanized. There were no requirements found for the rods to be mechanically cleaned (such as sandblasting) prior to galvanizing. It is assumed that the normal pickling process was followed. Other than the shop drawings, no documentation was found that indicated how or why the change to galvanizing was made. (Note: PB/RT JV's Engineer of Record stated that he did not know what was approved nor what was built, i.e. he was unaware that the A354 BD bolts were galvanized.)

Identical to the West half, the original 3 and 4 inch anchor bolts had rolled threads and are encased in a duct for most of their length. After stressing, the ducts were filled with grease and the exposed portions of the bolt and the nuts painted with the standard WSDOT three coat paint system.

Design Plan Sheet M 216 Section B from 2003 shows the 4 inch bolts were to be tensioned to 870 kips or 0.53Fu, and the 3 inch bolts to 713K or 0.78Fu, identical to the 1981 plans. An RFI from Kiewit General questioned the 713K pretension force on the 3 inch bolts being greater than the bolt's proof load of 627K. WSDOT issued a reply changing the force on the 3 inch bolts to 638K or 0.70Fu.

Note: The pretension forces of 0.53 Fu on the 4 inch bolts and 0.78 Fu on the 3 inch bolts were dictated by PB/RT JV calculations that indicate pretension loads of 0.5Fu and 0.72 Fu respectively. Considering short and long term pretension losses, the pretension forces specified forces insured that there would be no lift off at or near calculated maximum live loads.

The 2003 Design Plans and Specifications indicate that the 1 ½ diameter anchor bolts were to be ungalvanized A325 bolts. However, the 2007 Shop Drawing and as-built drawings indicate that these were changed to galvanized A354 BC bolts. There has been no indication found as to why the shop drawings show the bolts to be galvanized. As at the West half, the 1 ½ inch anchor bolts were encased in a greased duct for most of their length. The exposed portions of the bolt and the nuts were painted with the standard WSDOT three coat paint system. The design plans indicate that these bolts were not to be pretensioned.

The original 3 inch and 4 inch A354 BD bolts were supplied by Dyson through Thompson Metal Fab (TMF). The 2009 COC/CMO's and the 2004 MTR's for these bolts are in the Appendix. The COC/CMO's cover 18 – 3 inch bolts and 16 - 4 inch bolts that were delivered to the contractor Kiewit-General (KG) at the project site. The MTR's cover 20 – 3 inch bolts and 8 – 4 inch bolts. TMF found no MTR's for the other 8 – 4 inch bolts and as such, the supplier, alloy and

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mechanical properties are unknown. The bolts were of AISI 4140 alloy and met ASTM A354 BD specifications. They were heat treated, quenched (oil for 3 inch and water for 4 inch), tempered in a furnace at 1070F and straightened prior to the rolling of the threads. All rods were then galvanized. Mechanical Properties for the rods are given below.

Dyson A354 BD Bolts

Mechanical Property	Units	3 Inch Diameter Bolts	4 Inch Diameter Bolts*
Tensile	KSI	149.5	146.0
Yield 0.2%	KSI	126.9	124.0
Elong 2"	%	16.5	14.0
Red Area	%	51.7	42.0
Hardness	Rc	31.0	32.5

*These properties are for 8 of 16 bolts

IV.a. Problems During Construction

Several problems were encountered with the 3 inch and 4 inch ASTM A354 BD bolts during construction in 2009.

Pretensioning Method

The first problem was that the contractor attempted to pretension the bolts by torquing the nuts. However, there was enough friction between the nut and the bolt to cause twisting of the 20 ft. long bolts such that the plan force could not be achieved. To achieve the plan force in the bolts it was necessary to pretension the bolts with hydraulic jacks.

Bolt Failure - Thread Fit

The second problem concerned the fit of the threads between the nuts and the bolts. On October 22, 2008, during the stressing of the 4th set of 4 inch bolts, one of the 4 inch bolts failed. At approximately 60% of the required load the nut was spun down and the pressure on the jack was relieved. The nut then slipped and the threads on both the nut and the bolt were destroyed. It was determined that the threads on the nuts had been overcut out of tolerance and the rolled threads on the bolt created a smaller net diameter bolt than specified. DYSON Corporation, the supplier of these bolts, replaced two of the 4 inch bolts and accompanying nuts- but only after a great deal of work was done to investigate the cause of the failure. The two replacement bolts had rolled threads, were galvanized and had a 45 degree bevel at one end. The available WSDOT CMO's/ MTR's dated 5/29/2009 do not indicate the alloy type.

All of the remaining 4 inch and 3 inch bolt threads and nut threads were measured and 85% of the threads were found to be out of specification. WSDOT decided to replace all of the nuts, cut to fit the as-measured threads on the bolts. The nuts were installed black (not galvanized) and then painted with the WSDOT standard three coat system. A high pressure silicone, rust inhibiting, waterproof grease was specified to be applied to the threads prior to tensioning.

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Black nuts were specified to achieve a higher proof load (170 ksi - black vs. 150 ksi - galvanized) and to eliminate the potential variability of thickness of galvanizing on the threads.

Bolt Failures – Complete Fracture

The **third and most serious problem** occurred with the twelve 3 inch bolts. On the morning of Friday April 24, 2009, during the final fit-out of the draw pontoon system and approximately two weeks after the 3 inch bolts were pretensioned, K-G crews were applying the paint system to the washers, nuts and the exposed (non- greased and sheathed) portions of the bolts. They reported that one of the bolts – 5W/5WN - had completely fractured. WSDOT engineers directly involved in the construction of the Draw Pontoon stated that their belief is that the initial fractures occurred one week to two weeks after stressing. Two hours later it was reported that bolt 8W/7WN had completely fractured and that the other bolt 8E/7EN at the same box beam also appeared to be failing. This bolt failed later in the day. In all three instances the fracture was at the bottom of the bolt in the threaded portion of the bolt just above the nut. As stated in WSDOT RFI 01316, within the next week three more bolts were found to be completely fractured in the lower threaded portion of the bolts just above the lower nut.



Bolt 8E/7EN Prior to and after Failure

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9W/6EN Prior to Failure



10E/5EN

At the bottom of the 3 inch diameter anchor rods $\frac{1}{2}$ inch thick round washers were installed. These washers bear on and span the annular space of the CIP 4 inch diameter pipe sleeves. Some but

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not all of these washers bent and/or sheared under the pretension force applied to the bolt. In all cases in which the bolts completely fractured, the bolt was not perpendicular and the washers were noticeably bent and/or sheared.

Pictures above show Bolt 8E intact but with a deformed washer and then after its subsequent failure later in the same day. Note that the failed bolt is off center in the pipe sleeve. The combination of the bolt being off center in the hole combined with an undersized washer may have led to the failure of the washer and may have contributed to the failure of the bolt.

The next photo of bolt 9W was taken prior to bolt failure and shows the washer bent/sheared.

The last picture shows bolt 10E with a non-deformed washer. Records do not indicate if this bolt failed. However, records indicate that six total bolts completely failed and six did not – this matches with six washers that were severely bent or sheared and six washers that were not noticeably damaged or were slightly deformed.

The available plans for both 1982 West Half and 2009 East Half do not indicate washer size. The shop drawings for the West Half bottom washers call for rectangular plate washers **3-1/4" thick, 1'-0" X 1'-2"**, but the shop drawings available for the East Half do not detail the washers. The plate washers at West Half were measured as 1'-0" X 1'-2" but they are embedded in the concrete so their thickness could not be determined. The as built washers at the East Half are circular and measure **½ inch in thickness** – well below the 3-1/4 inch that appears to have been specified. The 3" diameter bolt washer failures were only a problem at the bolt bottom as the plate washer provided on the box girder at the top was thicker and the jacking plate had smaller diameter hole than the pipe sleeves.

Note: WSDOT (after the fact) calculations indicated that 2 inch thick washers of a higher tensile strength were necessary and 2" thick square plate washers were supplied for all 12- 3" replacement bolts.

IV.b. 2009 Failure Analysis – Dwight Co

After analyzing photos of the bolt fractures, the project mechanical engineer (construction) believed that the failures were either the result of overstress - that the washer failures caused asymmetrical loading on the bolt, with flexural tension plus axial tension overstressing the bolts and causing the bolt failures – or defective bolt material. He suggested that metallurgist Rainer Eckert of Northwest Labs in Seattle be engaged to ascertain the cause of failure. Mr. Eckert was contacted on Friday afternoon. When told the type of HS bolt and that they were galvanized - immediately said "hydrogen embrittlement". He stated that he was willing and available on Monday to begin forensic evaluation of the bolts. WSDOT's Assistant HCB Construction Engineer suggested that if there were hydrogen embrittlement (HE) issues with the 3 inch bolts that "it would be pretty likely the same issues exist with the 4 inch rods" and that if it could be found, it would be prudent to also test the 4 inch rod that had stripped out threads.

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However, it was eventually decided to engage Jay Dwight of Dwight Company, Inc. Welding Laboratory Service in Chehalis, WA who was immediately available to do the forensic investigation. On the evening of April 24, two of the three fractured bolts were delivered to Jay Dwight for forensic evaluation to ascertain the cause of the bolt failures and to recommend inspection details for corrective action (It is not known if the 4 inch rod with the stripped threads was found, but it was not delivered for testing.).

Dwight Company's report, dated Sunday April 26 and sent to WSDOT that afternoon, states that:

- The probable cause of failure of the 3" bolt assemblies is non-concentric loading during the final torque tensioning.
- Hydrogen damage was not present in the failed bolts at fracture interface or adjacent to fracture area.

Note: Although hydrogen damage was not seen, J. Dwight indicated to WSDOT that an SEM analysis would be necessary to state conclusively that there was no hydrogen embrittlement. This was not done at the time but was done by Lisin Metallurgical in 2013. There is further discussion of the Dwight Company's Report on pg 32, Section V.b. of this report.

Dwight Company also provided "Inspection Detail Recommendations" that included both visual and NDT inspection of all remaining bolts. The Dwight Co Report "Metallurgical Record of FW 3" Bolt Failures on East Half -2009" is in Appendix G.

The report included photos of the fractures. The fracture surfaces have an approximately 1/2 inch deep smooth half-moon fracture area that was called the "Initial Low Cycle Crack" and an approximate 2 3/4 inch deep rough fracture area that was called the "Final Fast Fracture Region".

IV.c. 2013 Fracture Analysis – Lisin Metallurgical

The photos of the fracture surfaces were very similar to those of the 3 inch diameter A354 BD bolts that fractured at Pier E2 of the San Francisco Oakland Bay Bridge (SFOBB). The SFOBB bolts were also 3 inch A354 BD bolts of similar length. These bolts were encased in a grouted sleeve and tensioned to 0.75Fu and seated at 0.70Fu. They began to fail ~6 days after stressing. The cause of these bolts failures is believed to be hydrogen embrittlement (HE).

Engineers from Bay Area Management Consultants (BAMC) visited the Hood Canal Bridge on June 28 and July 13 to determine if the experience with the HCB A354 BD bolts would provide information useful in evaluating the causes and possible remedies of the failures experienced with 2008 A354 BD anchor bolts of the SFOBB. There was interest in both the HCB black bolts installed on the West Half in 1982 and the galvanized bolts installed on the East Half in 2009. Reports of the two visits are in the Appendix to this section.

On the first HCB visit in June, BAMC engineers also visited Jay Dwight of Dwight Co to speak to Jay and to look at the two bolts no. 5 and 8 that Dwight CO had examined in 2009. Based on visual and optical microscopy, the failure morphology of these bolts appeared similar to that of the SFOBB bolts that had failed from HE in March 2013.

Since it would need to be confirmed by examination using a scanning electron microscope (SEM) before it could be concluded that the failure mechanism was in fact the same, permission was sought from WSDOT to do SEM analysis on the bolts. This permission was obtained from WSDOT near the end of July and Mark Lisin of LISIN Metallurgical Services in Milwaukie, OR was engaged to do failure analysis. The investigation included SEM analysis of bolts and hardness, chemical composition and Charpy testing of one bolt at -20F. Lisin was also engaged in January 2014 to do further material testing on bolts no. 5 and 8 that included additional Charpy tests at 20F and 40F, hardness tests adjacent to the fracture surface and characterization of the microstructure. Samples were taken at surface and mid-radius locations.

The Lisin Report 1 was completed on September 13, 2013 and Report 2 completed on January 31, 2014. Both Reports are contained in the Appendix.

The Lisin Report 1 states that:

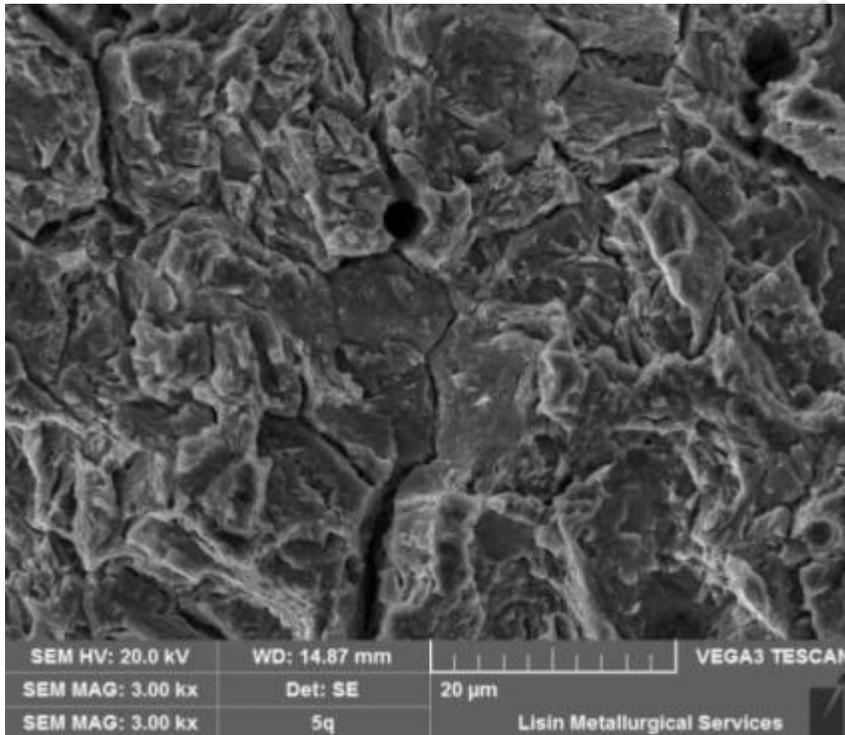
The mix of both ductile and brittle intergranular fracture suggests that the fracture initiation in the failed 3 inch diameter ASTM A354 BD high strength bolts was the result of mild hydrogen embrittlement.

Five likely contributing factors the HE failure were identified:

- 1) A high specified installation stress of 70% of the minimum specified ultimate tensile strength.
- 2) A likely increase in tensile stress due to washer deformation causing a bending load to be superimposed on the axial load.

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- 3) Use of a galvanized coating.
- 4) Minor corrosion of both the galvanized coating and the steel substrate was apparent, and the corrodant chlorine was detected in corrosion product deposits. Also, tension induced cracks were found in the zinc coating at the root of the threads. Hydrogen generation and HE /SCC cracking is possible under these conditions.
- 5) Use of a high strength material with non-homogeneous microstructure and limited fracture toughness.



BOLT 5 – Intergranular Fracture Surface

Above is the secondary electron image acquired from the fracture surface of Bolt 5. The location is approximately 1 to 2 mm below the thread root, within the crescent shaped band of smoother fracture near the fracture initiation. The location shown is the most pronounced example of intergranular fracture revealed by an extensive search.

Material Test Results Summary – Lisin Report 1 September 13, 2013

Property		2008 MTR's*	Current Tests (Ave)
Tensile	KSI	150	153
Yield	KSI	127	132
Elongation	%	16.5	17.0
Red of Area	%	51.7	55.0
Hardness	Rc	31.0	31.1**
Charpy -20F	ft-lb	not done	9.0***

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- * 2008 MTR's from Thompson Metal Fab, In Appendix to this Section. The material chemistry closely matched that given in the 2008 MTR's.
- ** Rc 26.0 at mid-radius and 35 near root of thread
- *** Varied 6.0-12.0, low enough to be out of the testing machine's verified range, and are given "for information only".

Material Test Results Summary – Lisin Report 2, January 31, 2014

**Table 1
HCB Bolt 5 Summary of Results**

Location	Charpy Values		Hardness, HRC	Microstructure
	+20 °F	+40 °F		
Surface	14.0	10.5	33, 32	Banded microstructure consisting of tempered martensite and other transformation products.
		14.0	31	
Mid-Radius	Mat'l Not Avail.	Mat'l Not Avail.	---	---

**Table 2
HCB Bolt 8 Summary of Results**

Location	Charpy Values		Hardness, HRC	Microstructure
	+20 °F	+40 °F		
Surface	14.0	16.0	30, 32	Banded microstructure consisting of tempered martensite and other transformation products.
	14.5	16.0	30, 31	
	15.0	18.0	31, 32	
Mid-Radius	17.0	15.0	32, 32	Banded microstructure consisting of tempered martensite and other transformation products.

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IV.d. Bolt Failures – Inelastic Deformations

Per the recommendations of Dwight Co., Mayes Testing Engineers were contracted to perform NDE inspection – magnetic particle testing and ultrasonic testing – on the six remaining intact bolts. Mayes Testing Engineers also assisted WSDOT in the visual inspection of the bolts. The full threads and 1 in of the shaft were prepared for inspection with focus on the thread roots. No cracks were found by the NDE inspections but visual inspection confirmed that all six bolts showed indications of inelastic deformation, and all six were found not acceptable for reuse.



Deformed Bolt 9E/6EN

IV.e. Bolt and Washer Replacements

Washers: All lower plate washers for all twelve of the 3 inch A354 BD bolts were replaced by the thickest plate possible – 2 inches- based on the thread limitations of the bolts. The plate material was specified to be 70ksi or greater and the plate was to be galvanized.

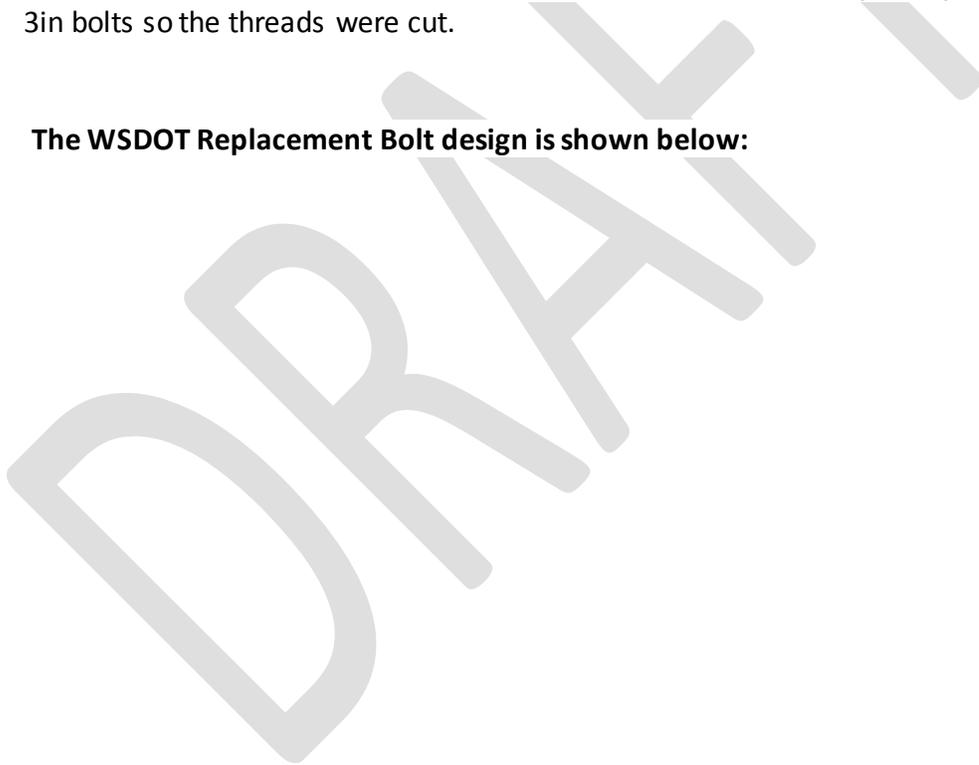
Fractured Bolts: The six 3 inch A354 BD bolts that completely fractured were replaced by spare rods that were located at the nearby WSDOT Lofall Maintenance Facility. There is no direct document verification available as to the origin of these bolts; however, WSDOT engineers are confident that these 6 bolts are from the original lot of 18 bolts from Dyson. There is a statement in email correspondence that they are “spare rods from the time the box girders were re-designed for the 4 inch rods.” Documents from Thompson Metal Fab indicate that they ordered twenty 3 inch A354 BD anchor

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rods from Dyson in 2004 and shipped 18 of these to Kiewit General in 2008. Twelve of these rods were used which would leave six as “spares”.

Deformed Bolts: For the six A354 BD 3 inch bolts that had indications of inelastic deformations, WSDOT directed that replacement bolts be galvanized, and that they be specified with a minimum Charpy of 15 ft-lbs at -20 F. Dyson, the supplier of the original rods could not make schedule, but Portland Bolt in Oregon was able to do so. However, Portland Bolt refused to galvanize the bolts because of their susceptibility to HE. On the recommendation of Portland Bolt, WSDOT specified that the bolts be made of a superior AISI 4340 alloy in lieu of the more usual AISI 4140 alloy for A354 BD bolts. Portland Bolt cited much higher toughness with little if any gain in hardness, and the better heat treatment performance of the 4340 alloy. It was also stated that this alloy would also be less susceptible to HE and SCC. The MTR for the 4340 material shows the following properties: Rockwell C = 35.5; Fu = 161ksi with RA = 56%; Fy = 144ksi with Elon =18%; CVN = 46 ft-lbs at -20F. (REF: MTR’s Appendix D). WSDOT wished the threads to be rolled after heat treatment but Portland Bolt did not have the capability to do such on 3in bolts so the threads were cut.

The WSDOT Replacement Bolt design is shown below:



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Six bolts were ordered by Kiewit from Portland Bolt on 5/27/09 March 29 with delivery promised 6/15/09. Six bolts were shipped by purchase order from Kiewit directly from Portland Bolt to Galvanizers Company for galvanizing.

Galvanizers Company only had the Portland Bolt/Kiewit's PO and invoice /delivery paperwork. They had neither written indication nor recollection that the bolts were to receive any special treatment. Therefore, they stated that the bolts would have gone through a regular pickling process, i.e. no mechanical cleaning, flash pickling or baking. Galvanizers Company also stated that they were not aware that Portland Bolt had refused to galvanize the bolts.



Bottom of 3 Inch Galvanized AISI 4140 Alloy A354 BD Bolt

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Bottom of 3 inch Galvanized AISI 4340 Alloy A354 BD Bolt

The A354 Bolts on the East Half were specified to be galvanized except for the top 7 inches of the threaded area. The nuts were specified to be black. This can be seen on the above WSDOT Design Drawing for the 3 inch replacement bolts. However, the As-Built Shop Drawings and visual inspection indicate a variety of conditions with respect to galvanizing of bolts and nuts.

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V. HE, SCC and Galvanizing of A354 BD Bolts

As previously mentioned, in 1982 the A 354 BD Guide Roller bolts at the West Half were installed black in greased ducts, and have been performing very well in a severely corrosive environment. The Design Plans for the East Half did not call for these bolts to be galvanized and WSDOT engineers were well aware of the susceptibility of galvanized A354 BD bolts to HE and Stress Corrosion Cracking (SCC), from both internal dictates and industry warnings e.g. Portland Bolt in Oregon. From 1998 to the present, the WSDOT Bridge Design Manual warned that “These (ASTM A354 BD) bolts should not be galvanized because of susceptibility to HE.” At the time there was concern that the failures may have been caused by hydrogen embrittlement, and Portland Bolt refused to provide galvanized A354 BD bolts due to their propensity for HE.

So, why were the same bolts on the East Half galvanized? And why, when six of these bolts completely fractured, were the replacement bolts galvanized?

V.a. Galvanizing - Original Bolts (Dyson)

It is not clear why the original bolts were galvanized. Those contacted who were involved in the construction of the bridge do not know, and no change order documentation was found. The 2009 Thompson Metal Fab Shop Drawings do show these bolts to be galvanized.

One possible explanation is that the fact that most all structural steel was galvanized, including most steel on the Design Plan Sheet that detailed the bolts, led to the error of calling out the bolts to be galvanized on the shop drawings – and that this error was not picked up in shop drawing review.

V.b. Galvanizing - Replacement Bolts (Portland Bolt)

From a study of available records, and from direct statements from those involved at the time, it appears that when the bolt failures occurred there was intense pressure to make schedule, and that the easiest way forward was not to change anything, i.e. if possible, stay with galvanized A354 BD bolts.

The fractures in the bolts occurred shortly before the planned closure to begin May 1, 2009, so time was critical. The float-out of the existing East Half and the float-in of the East Half replacement was to be done in a six week period starting May 1, 2009. It is stated in the WSDOT Post Construction Report that there was a great deal of pressure not just to meet, but to beat schedule. There was political pressure, public pressure and the pressure of the contractor’s financial incentives. The WSDOT “Hood Canal Bridge, East-Half Replacement and West-Half Retrofit Project, Post-Construction Report” states:

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“Many decisions were being made at a high level relative to planning for the bridge to re-open, which was being influenced by the contractor’s incentive pay as well as by increasing pressure from the public. ...many did not agree with the early opening date because they could not complete the full testing as intended by the contract requirements. There was a sense of many technical personnel being fairly involved throughout the project, but (that) there was a significant change in the level of their involvement when float-in closure was underway.”

And that -

“The contract provided the contractor an incentive by paying them \$75,000 for each day the bridge opened earlier than the allotted 42 days for up to 8 days, equating to a \$600,000 total incentive. ... the bridge was opened 8 days early on June 3, 2009, which included 2 1/4 days of working days that were lost due to stormy weather conditions (high winds). The contractor was able to receive their full incentive pay.”

Also, it was noted in the summary of findings in the 2009 Dwight Co. failure analysis that the findings were *“...based on the metallurgy observed in this brief investigation.”* In talks with J. Dwight he stated that the State was very rushed- *“something was pushing them”*- and that in the time frame allotted he did the key tasks he was asked to do, i.e. determining probable cause of failure and if hydrogen damage was evident at the fracture surface. He was not told that they were delayed fractures, but that the failure occurred during torqueing of the nut in a standard install procedure. He was surprised to hear that the nuts were not torqued, but that the bolts were jacked and the nuts spun down.

V.c. Bolt Failures – Hydrogen Embrittlement (HE) induced by Internal or External Hydrogen

HE and Stress Corrosion Cracking (SCC)

HE can occur in high strength low alloy martensitic steels such as ASTM A354 Grade BD when there exists high levels of hydrogen in the material. This can either be internal hydrogen resulting from manufacture practices and/or application of protective coatings such as hot dip galvanizing. It could also be infusion of external hydrogen into the material from corrosion after manufacture and coating. When the source of hydrogen is external failure of the material is termed to be by (hydrogen assisted) SCC.

For SCC to occur three combined actions must be present: High static tensile stress, a corrosive environment and a susceptible material. SCC is believed to be a galvanic corrosion process with a crack, pit or crevice developing at anodic sites. Tension forces concentrate at the tip of the crack, resulting in the formation of fresh metal surfaces and further deterioration by pitting corrosion.

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For uniform corrosion localized anodic and cathodic sites do not exist. With this form of attack the metal is gradually and uniformly changed to ferrous ions from the outer surface inwards. Consequently, the reduction of cross section is uniform and the inner portion of the metal is unaltered by the process. However, if variations in electrode potential along the metal surface allow separate corrosion cell to develop, then localized corrosion can occur.

Localized corrosion is generally associated with the presence of and the localized breakdown of a protective coating on the metal surface. A mechanism of pitting or crevice corrosion will occur in the presence of aggressive ions such as chloride. A pit is formed at an area where chloride ions locally weaken the coating that protects the steel. The anode is established where the coating is destroyed and the surrounding steel becomes the cathode. While pitting can cause little overall metal loss, the effects can be significant due to the localized reductions in the metal cross section and increased stress on the unaltered section with stress concentration at the pit area.

For high strength low alloy martensitic steels such as ASTM A354 Grade BD, Stress Corrosion Cracking (SCC) is most likely to take the form of hydrogen embrittlement. This involves the migration of atomic hydrogen into the metal lattice where hydrogen molecules are formed producing internal pressure in the metal. Hydrogen is exceptionally mobile and quickly penetrates into any recently formed cracks, lesions or material surface discontinuities, which become high stress areas. In general, any process producing atomic hydrogen at the steel surface can induce considerable hydrogen absorption in the steel. Cracks will promulgate through the component surface, weakening the component due to the loss of cross-section area. Since corrosion reactions are generators of hydrogen, care in choosing the proper coating to prevent corrosion is important.

Metallic coatings such as zinc have relatively low corrosion potential and can isolate the metal from the environment and theoretically prevent SCC. However, the possibility of the coating being penetrated by imperfect application or by mechanical damage in service must be taken into account. For this reason zinc is a popular coating for low strength carbon steel - if the zinc coating is compromised locally causing underlying steel to be exposed, the steel will be cathodically protected - the zinc coating being the sacrificial anode and the steel base metal being the cathode. However, the electrode potential involved in this galvanic reaction will also encourage hydrogen evolution and adsorption of hydrogen into the steel matrix. For high strength low alloy martensitic steels such as ASTM A354 Grade BD, if this occurs at a location of localized corrosion/pitting or in a highly stressed and potentially notched location such as the root of the thread under the nut, this may lead to hydrogen embrittlement.

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Note: Concrete or cement grout provides good corrosion protection to bare steel. However, the use of concrete as protection to galvanized high strength steel has the potential to produce SCC /HE of the HS steel. This is due to the well-known fact that zinc will actively corrode in a wet, caustic environment thus generating high levels of hydrogen. The Post Tensioning Institute (PTI, 1998) recommendations prohibit contact between cement grout and galvanized strands (in the stressed zone) because of the risk of (SCC) hydrogen embrittlement.

Corrosion Protection of Bolts Prior to Tensioning

Construction records such as MTR's, photos, WSDOT Monthly Reports and email correspondence indicate that the A354 anchor bolts were very likely not protected from corrosion and were subjected to water from rain and condensation for an extended period of time – up to 14 months - prior to stressing. As such, the HE assisted failures of the six 3 in bolts could have occurred from a combination of excess internal and external hydrogen.

The approximate duration during which the bolts were installed and unprotected is derived from the summary of the placement of the A5354 BD Rods in the Draw Span pontoons (Ref: Appendix I). The key dates with corresponding activities are:

- December 2004 to March 2005- Bolts manufactured, zinc coated and tested by Dyson Corp, Painesville, OH
- May 31, 2005- Bolts delivered to Thompson Metal Fab Inc, Vancouver , WA
- February 26, 2008 – Bolts are shipped to the contractor Kiewit-General.
- June 8, 2008-Lift Span is delivered to Todd Shipyards where the Draw span is being assembled and outfitted
- August 13, 2008- Lift span is shown installed and bolts are shown not to be protected with no nut at top of bolt. The bolts would have needed to be installed prior to the installation of the Lift Span as the overhead clearance with the Lift Span in place does not allow the bolts to be installed without bending the bolts. Ref photos below.
- March 12 to April 17, 2009-Begin and end bolt tensioning
- April 24, 2009 – First fractured bolt found and two others fracture
- April 30, 2009- Three more bolts fracture

The duration range that the bolts were unprotected from contact with water prior to fracture is indicated to be a minimum of 9 months and a maximum of 14 months. Note that the bolts were stored at Thompson Metal Fab (TMF) for 2 years and 9 months prior to deliver to Kiewit-General. Brian Brace of TMF indicated that during this time the bolts were in protective storage in their warehouse.

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No Nut at Left Hand Bolt-August 13, 2008



Lift Span Installed – August 13, 2008

Other indications that water may have been present on the rods are:

- The Lisin Report 1 (Ref: Appendix F) states that deposits found on the washers consist primarily of zinc corrosion products and that substantial chlorine deposits were also detected. The Report further states that “Chlorine is a potent

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corrodant of alloy steels when present with moisture.... Corrosion of zinc coated steel can result in hydrogen generation and subsequent hydrogen embrittlement.”

- Shown below is a photo of the bottom threads and shank of a failed rod taken three days after it was found to be fractured. Corrosion can be seen on the threads and the shank of the rod. It is also clear that the rod is unprotected – i.e. there is no indication of paint or grease.



- As stated in Section IV.a of this report, on October 22, 2008 during the stressing of the one of the 4 inch bolts the nut slipped and the threads on both the nut and the bolt were destroyed. This precipitated removing all of the 3 inch and 4 in nuts to inspect and measure threads. WSDOT decided to replace all of the nuts, cut to fit the as-measured threads on the bolts. As shown in the bolt placement summary, the last of these new bolts arrived March 11, 2009. Therefore, a worst case scenario would have been all nuts off from October to March.

SCC Precautions

Susceptibility of HS lean alloy steels such as A354 BD to SCC can be eliminated or controlled by a variety of methods that include:

- **Use of rolled vs. cut threads:** Cut threads tend to cause a sharper root than rolled threads, with the probability of more defects on or beyond the root. So the time taken for a sharp-fronted crack to initiate and grow to the critical size may be shorter in cut threads than in rolled ones due to reasons such as SCC. The rolled threads have less of a sharp root and if they are rolled after heat

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treatment they retain large compressive stresses in the thread roots which mitigate the applied tensile stresses.

Accelerated testing in environments aggressive for the specific material have shown that fastener threads that are rolled after strengthening heat treatments have improved resistance to stress corrosion cracking (SCC) initiation. For example, intergranular SCC was produced in one day when machined (cut) threads of high-strength steel ASTM A354 BD were exposed to an aggressive aqueous environment containing 8 wt % boiling ammonium nitrate and stressed to about 40 % of the steel's yield strength. In similar testing conditions, bolts that were thread rolled before heat treatment (quench and temper) had similar high susceptibility to SCC. However, threads rolled after the strengthening heat treatment exhibited no SCC after a week of exposure, even when stressed to 100 % of the alloy yield strength.This beneficial effect of the optimum thread rolling process (i.e., threads rolled after the strengthening heat treatment) is due to the retention of large residual compressive stresses in the thread roots (notches), which mitigate the applied notch tensile stresses resulting from joint design preloads. The main thing that was learned by the technical literature searches regarding rolled threads is that they have always improved resistance to SCC and fatigue. That “...rolled threads are expected to increase the resistance to HE/SCC of the anchor rods on the SAS. While the hardened material at the root of the thread will have a low K_{ISCC} , this is not important since the high compressive residual stresses at the root of the threads prevent crack initiation or propagation in this area.” (Ref: ASTM Volume 3, Issue 7, July 2006 “Optimum Thread Rolling Process that Improves SCC Resistance” ; and in Appendix G, Jeff Gorman, Dominion Engineering, Inc – “Review of the Use of Cold Rolled Threads for Anchor Rods on the San Francisco Oakland Bay Bridge (SFOBB)” discusses the use of rolled vs. cut threads.)

- **Use of an alloy with greater toughness that allows more complete and uniform hardening:** E.g. using AISI 4340 vs. 4140 alloy. The *tougher* the material, the more it is capable of resisting SCC. The harder the material the more susceptible it is to SCC.
- **Minimizing applied stress:** e.g. Pretension $\leq 0.5 F_u$. The greater the hydrogen concentration becomes, the lower the critical stress, or lower the hydrogen concentration, the higher the critical stress at which failure may occur.
- **Control corrosion utilizing protection that minimizes electric potential and/or eliminates contact with hydrogen compounds (e.g. water):** First - Do not galvanize the material. Then: use grease with the virtue of its dielectric properties; paint coating(s) that protects the underlying metal largely by virtue of their high electrical resistance which restricts the passage of current from the anode to the cathode; and/or dehumidification that eliminates hydrogen compounds. Paints are effective at restricting SCC, particularly when they incorporate inhibitors that can inhibit any solution that does find its way to the

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metal. Paints can also protect and passivate zinc coatings. Note that concrete or cement grout provides good corrosion protection to bare steel. However, there is concern regarding the durability of galvanized high strength steel bolts and strands in contact with concrete or cementitious grout - that concrete as protection to galvanized high strength steel represents a risk of hydrogen induced stress corrosion for high strength bolts and prestressing steel. These concerns are based on the fact that zinc reacts with wet concrete to form calcium hydroxide accompanied by the production of hydrogen and in the process. Depending on its thickness and condition, the zinc coating can inhibit the passage of this hydrogen into the steel but if there are existing holidays in the zinc coating or if enough of the zinc layer is dissolved in the reaction, the hydrogen can penetrate into the steel. The Post Tensioning Institute (PTI, 1998) recommendations prohibit contact between cement grout and galvanized strands because of the risk of (SCC) hydrogen embrittlement. (Ref" NCHRP Report 675 "LRFD Metal Loss and Service-Life Strength Reduction Factors for Metal-Reinforced Systems"; FIB Technical report "Effect of Zinc on Prestressing Steel, Feb 2012) .

Fracture Mechanics Analysis

The fracture mechanics table and graph below covers four ASTM A354 rods: the two from the San Francisco Oakland Bay Bridge (SFOBB) both came from Dyson, one in 2008 and the other in 2010; and the two from the Hood Canal Floating Bridge (HCB) are the original bolts from Dyson in 2005 and the replacement bolts from Portland Bolt in 2009.

The fracture mechanics graph and table below illustrate the estimated crack depth vs. the applied nominal stress at which brittle fracture may occur in a threaded rod. The fracture driving force is the stress intensity factor (K_I) calculated based on the level of applied stress (σ) and the depth of an edge crack (a) initiated from the thread root. The fracture resistance is the fracture toughness of steel (K_{Ic}) estimated from Charpy V-notch (CVN) impact test data of material samples removed from the rods. The calculations cover a range of nominal tensile stress varying from $0.35F_u$ to $0.85F_u$, where F_u is the nominal tensile strength of 140 ksi of the ASTM A354 Grade BD rods. The graph includes three K_{Ic} values for the original rods and the Portland Bolt replacement rods of the HCB. The table also includes two K_{Ic} values for the 2008 and 2010 rods of the SFOBB.

The fracture mechanics analysis is for comparative purposes. Calculations are based on uniform nominal stresses that are used to calculate stress intensity factor for the assumed crack configuration. Non-uniform stress from bending stresses caused by bolt eccentricity or residual stress due to rolled vs. cut threads were not considered. The

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analysis considers only the state at the time of fracture, regardless of the process that caused crack initiation.

As shown in the graph and the table, the higher the loading stress, the smaller the crack depth needed to cause a rupture; similarly, the lower the fracture toughness, the smaller the crack depth needed to cause a rupture.

In the graph, each solid curved line represents the increase of K_I with the increase of crack depth at a specific stress level; and the horizontal dashed lines represent the three K_{Ic} values estimated from CVN data. The intersecting points between the solid lines and the dashed lines mark the combinations of applied stress level (σ) and crack depth (a) at which brittle fracture should be expected for each toughness value (K_{Ic}).

It should be noted that all the K_I curves exhibit a “plateau” in the region of crack depth varying between 0.05" and 0.25". This is likely due to the combined effects of decrease in local stress concentration due to thread and increase in crack depth. After the crack depth goes beyond this range, K_I consistently increases with increasing crack depth because the local stress concentration due to thread is no more effective. This plateau appears in the form of “jumps” in the table format.

In the table, the highlighted cells correspond to the combinations of applied stress level (σ) and crack depth (a) that result in a stress intensity factor (K_I) close to (within +/-0.5 ksi√in) the fracture toughness (K_{Ic}) of one of the four rods. Explanations for the color coding in the table are provided below.

Pink = HCB 2005 original rods of AISI 4140 alloy made by DYSON from Thompson Metal Fab (TMF); K_{Ic} = 37 ksi√in at service temperature of -37°F estimated from the transition region CVN- K_{Ic} correlation (average CVN = 9.5 ft-lb at -20°F). Material properties are based on Lisin Tests Report 1 and 2 and MTRs from TMF (Ref. Appendix).

Orange = HCB 2005 original rods of AISI 4140 alloy made by DYSON from Thompson Metal Fab (TMF); K_{Ic} = 74 ksi√in for service temperatures at or higher than 20°F estimated from the upper-shelf CVN- K_{Ic} correlation (average CVN = 14.90 ft-lb at 20°F, and 14.92 ft-lb at 40°F, respectively). Material properties are based on Lisin Tests Report 1 and 2 and MTRs from TMF (Ref. Appendix).

Blue = HCB 2009 replacement rods of AISI 4340 alloy made by Portland Bolt (PB); K_{Ic} = 82 ksi√in at service temperature of -19°F estimated from the transition region CVN- K_{Ic} correlation (average CVN = 46 ft-lb at -20°F). These rods have significantly higher fracture toughness and may be expected to exhibit similar characteristics as the 2013 SFOBB rods. (For material properties Ref. PB MTR's in Appendix)

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Yellow = SFOBB 2008 rods of AISI 4140 alloy made by DYSON; $K_{Ic} = 67$ ksi√in at service temperature of 40°F estimated from the upper-shelf CVN- K_{Ic} correlation (average CVN = 13.5 ft-lb at 40°F).

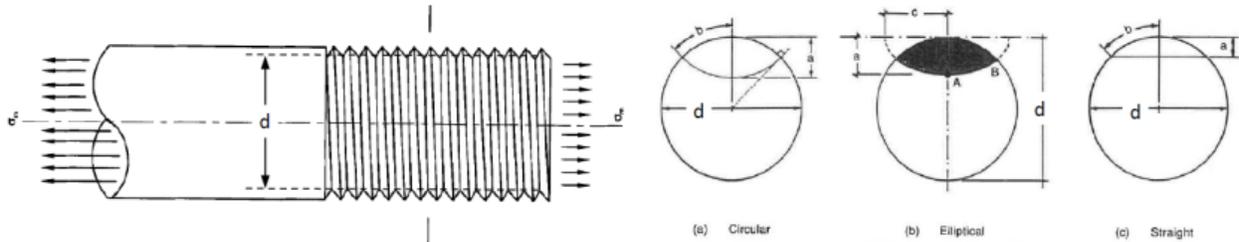
Green = SFOBB 2010 rods of AISI 4140 alloy made by DYSON; $K_{Ic} = 145$ ksi√in at service temperature of 40°F estimated from the upper-shelf CVN- K_{Ic} correlation (average CVN = 37 ft-lb at 40°F).

The fracture mechanics graph and table are shown below and in the following five pages.

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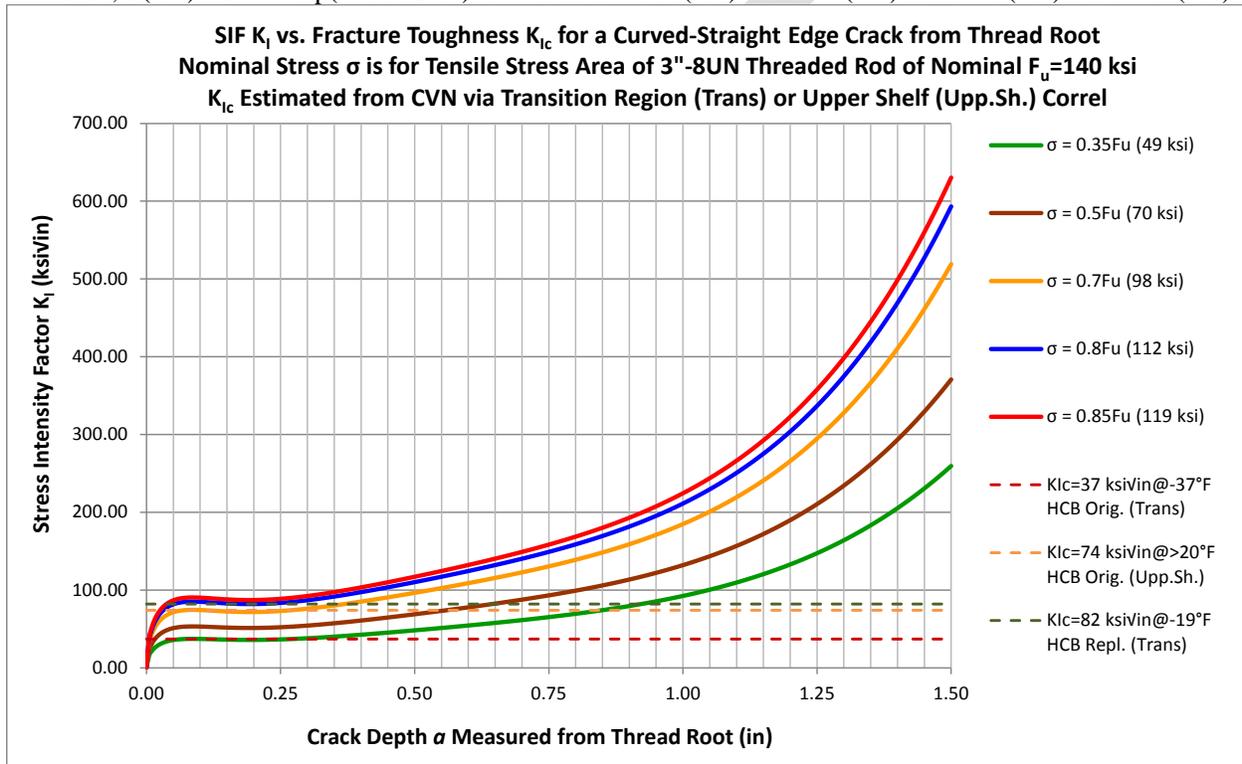
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Calculated K_I vs. K_{Ic} at Fracture for a Curved-straight Edge Surface Crack from Thread Root
 (3"-8UN Rod, nominal $F_u=140$ ksi, a =crack depth, σ =nominal stress for tensile stress area)



$$K_I = F(a/d)\sigma\sqrt{\pi a}$$

where, $F(a/d) = 2.043\exp(-31.332a/d) + 0.6507 + 0.5367(a/d) + 3.0469(a/d)^2 - 19.504(a/d)^3 + 45.647(a/d)^4$



Notes:

- 1) Fracture toughness K_{Ic} is estimated from CVN and tensile test data (IMR KHA Report Nos. 201311742 and 201400457) per K_{Ic} -CVN correlations in “Barsom, J.M. and Rolfe, S.T., *Fracture and Fatigue Control in Structures*, 3rd Ed., ASTM, 1999”. For HCB original rods, K_{Ic} was estimated for transition region and upper-shelf based on CVN data at -20°F, 20°F, and 40°F. For HCB replacement rods, K_{Ic} was estimated for transition region only since CVN data was only available at -20°F.
- 2) Stress intensity factor K_I is calculated per solution in “Liu, A.F., Behavior of Fatigue Cracks in a Tension Bolt, Structural Integrity of Fasteners, ASTM STP 1236, 1995”. Crack depth a is measured from thread root, of front changing from circular to straight near $a/D=0.5$.
- 3) Rod and thread dimensions are taken from ASME B1.1-2003 Unified Inch Screw Threads, thread type: 3" - 8 UN 2A for HCB.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

Calculated K_I vs. K_{Ic} at Fracture for a Curved-straight Edge Surface Crack from Thread Root for 3"-8UN Rod, $F_u = 140$ ksi, a = crack depth, σ = nominal stress for tensile stress area															
(Listed values are stress intensity factor K_I of sharp cracks of depth a measured from thread root at different nominal stress levels)															
K_{Ic} Estimation from CVN			(Transition region CVN- K_{Ic} correlation)					(Upper shelf CVN- K_{Ic} correlation)							
Fracture Toughness K_{Ic} :			HCB Original at -37°F: 37 ksi√in					HCB Original at >20°F: 74 ksi√in					SFOBB 2010 at 40°F: 145 ksi√in		
			HCB Replacement (Portland) at -19°F: 82 ksi√in										SFOBB 2008 at 40°F: 67 ksi√in		
Note: For the Hood Canal Bridge (HCB) Portland replacement rods, K_{Ic} was estimated for transition region only since CVN data was only available at -20°F. The 4340 alloy may be expected to exhibit similar characteristics as the SFOBB 2010 replacement rod specification.															
a (in)	a/d ($d=2.8486"$)	$F(a/d)$	$K_I = F(a/d)\sigma\sqrt{a}$ (ksi√in), where $F(a/d) = 2.043\exp(-31.332a/d) + 0.6507 + 0.5367(a/d) + 3.0469(a/d)^2 - 19.504(a/d)^3 + 45.647(a/d)^4$												
			$\sigma = 0.35F_u$ (49 ksi)	$\sigma = 0.4F_u$ (56 ksi)	$\sigma = 0.45F_u$ (63 ksi)	$\sigma = 0.5F_u$ (70 ksi)	$\sigma = 0.55F_u$ (77 ksi)	$\sigma = 0.6F_u$ (84 ksi)	$\sigma = 0.65F_u$ (91 ksi)	$\sigma = 0.7F_u$ (98 ksi)	$\sigma = 0.75F_u$ (105 ksi)	$\sigma = 0.8F_u$ (112 ksi)	$\sigma = 0.85F_u$ (119 ksi)		
0.000	0.000	2.694	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.001	0.000	2.672	7.34	8.39	9.43	10.48	11.53	12.58	13.63	14.67	15.72	16.77	17.82		
0.002	0.001	2.650	10.29	11.76	13.23	14.70	16.17	17.64	19.11	20.58	22.05	23.52	24.99		
0.003	0.001	2.628	12.50	14.29	16.07	17.86	19.64	21.43	23.22	25.00	26.79	28.57	30.36		
0.004	0.001	2.607	14.32	16.36	18.41	20.45	22.50	24.54	26.59	28.63	30.68	32.73	34.77		
0.005	0.002	2.585	15.88	18.15	20.41	22.68	24.95	27.22	29.49	31.75	34.02	36.29	38.56		
0.006	0.002	2.564	17.25	19.72	22.18	24.65	27.11	29.57	32.04	34.50	36.97	39.43	41.90		
0.007	0.002	2.544	18.48	21.12	23.76	26.40	29.04	31.69	34.33	36.97	39.61	42.25	44.89		
0.008	0.003	2.523	19.60	22.40	25.20	28.00	30.80	33.60	36.40	39.20	42.00	44.80	47.60		
0.009	0.003	2.503	20.62	23.57	26.51	29.46	32.41	35.35	38.30	41.24	44.19	47.14	50.08		
0.010	0.004	2.483	21.56	24.64	27.72	30.80	33.89	36.97	40.05	43.13	46.21	49.29	52.37		
0.011	0.004	2.463	22.44	25.64	28.85	32.05	35.26	38.46	41.67	44.87	48.08	51.28	54.49		
0.012	0.004	2.443	23.25	26.57	29.89	33.21	36.53	39.85	43.17	46.49	49.81	53.13	56.46		
0.013	0.005	2.424	24.00	27.43	30.86	34.29	37.72	41.15	44.58	48.01	51.44	54.87	58.29		
0.014	0.005	2.405	24.71	28.24	31.77	35.30	38.83	42.36	45.90	49.43	52.96	56.49	60.02		
0.015	0.005	2.386	25.38	29.00	32.63	36.25	39.88	43.51	47.13	50.76	54.38	58.01	61.63		
0.016	0.006	2.367	26.00	29.72	33.43	37.15	40.86	44.58	48.29	52.01	55.72	59.44	63.15		
0.017	0.006	2.349	26.60	30.39	34.19	37.99	41.79	45.59	49.39	53.19	56.99	60.79	64.59		
0.018	0.006	2.330	27.15	31.03	34.91	38.79	42.67	46.55	50.43	54.31	58.18	62.06	65.94		
0.019	0.007	2.312	27.68	31.63	35.59	39.54	43.50	47.45	51.40	55.36	59.31	63.27	67.22		
0.020	0.007	2.294	28.18	32.20	36.23	40.25	44.28	48.31	52.33	56.36	60.38	64.41	68.43		
0.021	0.007	2.276	28.65	32.74	36.84	40.93	45.02	49.12	53.21	57.30	61.40	65.49	69.58		
0.022	0.008	2.259	29.10	33.26	37.41	41.57	45.73	49.88	54.04	58.20	62.36	66.51	70.67		
0.023	0.008	2.242	29.52	33.74	37.96	42.18	46.40	50.61	54.83	59.05	63.27	67.49	71.70		
0.024	0.008	2.224	29.93	34.20	38.48	42.76	47.03	51.31	55.58	59.86	64.13	68.41	72.69		
0.025	0.009	2.207	30.31	34.64	38.97	43.31	47.64	51.97	56.30	60.63	64.96	69.29	73.62		
0.026	0.009	2.191	30.68	35.06	39.44	43.83	48.21	52.59	56.98	61.36	65.74	70.12	74.51		
0.027	0.009	2.174	31.03	35.46	39.89	44.32	48.76	53.19	57.62	62.05	66.49	70.92	75.35		
0.028	0.010	2.158	31.36	35.84	40.32	44.80	49.28	53.76	58.24	62.72	67.20	71.67	76.15		
0.029	0.010	2.142	31.67	36.20	40.72	45.25	49.77	54.30	58.82	63.35	67.87	72.40	76.92		
0.030	0.011	2.125	31.97	36.54	41.11	45.68	50.24	54.81	59.38	63.95	68.51	73.08	77.65		
0.031	0.011	2.110	32.26	36.87	41.48	46.08	50.69	55.30	59.91	64.52	69.13	73.74	78.34		
0.032	0.011	2.094	32.53	37.18	41.83	46.47	51.12	55.77	60.42	65.06	69.71	74.36	79.01		
0.033	0.012	2.078	32.79	37.48	42.16	46.85	51.53	56.21	60.90	65.58	70.27	74.95	79.64		
0.034	0.012	2.063	33.04	37.76	42.48	47.20	51.92	56.64	61.36	66.08	70.80	75.52	80.24		
0.035	0.012	2.048	33.28	38.03	42.78	47.54	52.29	57.04	61.80	66.55	71.30	76.06	80.81		
0.036	0.013	2.033	33.50	38.29	43.07	47.86	52.64	57.43	62.21	67.00	71.79	76.57	81.36		
0.037	0.013	2.018	33.71	38.53	43.35	48.16	52.98	57.80	62.61	67.43	72.25	77.06	81.88		
0.038	0.013	2.003	33.92	38.76	43.61	48.46	53.30	58.15	62.99	67.84	72.68	77.53	82.37		
0.039	0.014	1.989	34.11	38.99	43.86	48.73	53.61	58.48	63.35	68.23	73.10	77.97	82.85		
0.040	0.014	1.975	34.30	39.20	44.10	49.00	53.90	58.80	63.70	68.60	73.50	78.40	83.30		
0.041	0.014	1.960	34.48	39.40	44.33	49.25	54.18	59.10	64.03	68.95	73.88	78.80	83.73		
0.042	0.015	1.946	34.64	39.59	44.54	49.49	54.44	59.39	64.34	69.29	74.24	79.19	84.14		
0.043	0.015	1.933	34.80	39.78	44.75	49.72	54.69	59.66	64.64	69.61	74.58	79.55	84.52		
0.044	0.015	1.919	34.96	39.95	44.94	49.94	54.93	59.93	64.92	69.91	74.91	79.90	84.90		
0.045	0.016	1.905	35.10	40.12	45.13	50.15	55.16	60.18	65.19	70.20	75.22	80.23	85.25		
0.046	0.016	1.892	35.24	40.27	45.31	50.34	55.38	60.41	65.45	70.48	75.51	80.55	85.58		
0.047	0.016	1.879	35.37	40.42	45.48	50.53	55.58	60.64	65.69	70.74	75.80	80.85	85.90		
0.048	0.017	1.865	35.50	40.57	45.64	50.71	55.78	60.85	65.92	70.99	76.06	81.14	86.21		
0.049	0.017	1.853	35.62	40.70	45.79	50.88	55.97	61.05	66.14	71.23	76.32	81.41	86.49		
0.050	0.018	1.840	35.73	40.83	45.94	51.04	56.14	61.25	66.35	71.46	76.56	81.66	86.77		
0.052	0.018	1.815	35.94	41.07	46.20	51.34	56.47	61.61	66.74	71.87	77.01	82.14	87.27		
0.054	0.019	1.790	36.12	41.28	46.44	51.60	56.77	61.93	67.09	72.25	77.41	82.57	87.73		
0.056	0.020	1.766	36.29	41.48	46.66	51.84	57.03	62.21	67.40	72.58	77.77	82.95	88.14		
0.058	0.020	1.742	36.44	41.65	46.85	52.06	57.26	62.47	67.68	72.88	78.09	83.29	88.50		
0.060	0.021	1.719	36.57	41.80	47.02	52.25	57.47	62.70	67.92	73.15	78.37	83.60	88.82		
0.062	0.022	1.697	36.69	41.93	47.17	52.42	57.66	62.90	68.14	73.38	78.62	83.86	89.11		
0.064	0.022	1.675	36.79	42.05	47.31	52.56	57.82	63.08	68.33	73.59	78.84	84.10	89.36		
0.066	0.023	1.653	36.88	42.15	47.42	52.69	57.96	63.23	68.50	73.77	79.04	84.31	89.58		
0.068	0.024	1.632	36.96	42.24	47.52	52.80	58.08	63.36	68.64	73.92	79.20	84.48	89.76		
0.070	0.025	1.611	37.03	42.32	47.61	52.90	58.19	63.48	68.77	74.06	79.35	84.64	89.93		
0.072	0.025	1.591	37.08	42.38	47.68	52.98	58.28	63.57	68.87	74.17	79.47	84.77	90.06		
0.074	0.026	1.572	37.13	42.44	47.74	53.05	58.35	63.65	68.96	74.26	79.57	84.87	90.18		
0.076	0.027	1.552	37.17	42.48	47.79	53.10	58.41	63.72	69.03	74.34	79.65	84.96	90.27		
0.078	0.027	1.534	37.20	42.51	47.83	53.14	58.46	63.77	69.08	74.40	79.71	85.03	90.34		
0.080	0.028	1.515	37.22	42.54	47.86	53.17	58.49	63.81	69.13	74.44	79.76	85.08	90.40		

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

a (in)	a/d (d=2.8486")	F(a/d)	$K_1 = F(a/d)\sigma_v n a$ (ksi/in), where $F(a/d) = 2.043\exp(-31.332a/d) + 0.6507 + 0.5367(a/d) + 3.0469(a/d)^2 - 19.504(a/d)^3 + 45.647(a/d)^4$										
			$\sigma = 0.35F_u$ (49 ksi)	$\sigma = 0.4F_u$ (56 ksi)	$\sigma = 0.45F_u$ (63 ksi)	$\sigma = 0.5F_u$ (70 ksi)	$\sigma = 0.55F_u$ (77 ksi)	$\sigma = 0.6F_u$ (84 ksi)	$\sigma = 0.65F_u$ (91 ksi)	$\sigma = 0.7F_u$ (98 ksi)	$\sigma = 0.75F_u$ (105 ksi)	$\sigma = 0.8F_u$ (112 ksi)	$\sigma = 0.85F_u$ (119 ksi)
0.450	0.158	0.778	45.30	51.77	58.24	64.71	71.19	77.66	84.13	90.60	97.07	103.54	110.01
0.455	0.160	0.778	45.58	52.10	58.61	65.12	71.63	78.14	84.66	91.17	97.68	104.19	110.70
0.460	0.161	0.779	45.87	52.42	58.97	65.53	72.08	78.63	85.19	91.74	98.29	104.84	111.40
0.465	0.163	0.779	46.16	52.75	59.34	65.94	72.53	79.12	85.72	92.31	98.91	105.50	112.09
0.470	0.165	0.780	46.44	53.08	59.71	66.35	72.98	79.62	86.25	92.89	99.52	106.16	112.79
0.475	0.167	0.781	46.73	53.41	60.09	66.76	73.44	80.12	86.79	93.47	100.15	106.82	113.50
0.480	0.169	0.782	47.03	53.74	60.46	67.18	73.90	80.62	87.34	94.05	100.77	107.49	114.21
0.485	0.170	0.782	47.32	54.08	60.84	67.60	74.36	81.12	87.88	94.64	101.40	108.16	114.92
0.490	0.172	0.783	47.61	54.42	61.22	68.02	74.82	81.62	88.43	95.23	102.03	108.83	115.63
0.495	0.174	0.784	47.91	54.75	61.60	68.44	75.29	82.13	88.98	95.82	102.67	109.51	116.35
0.500	0.176	0.785	48.21	55.09	61.98	68.87	75.76	82.64	89.53	96.42	103.30	110.19	117.08
0.505	0.177	0.786	48.51	55.44	62.37	69.30	76.22	83.15	90.08	97.01	103.94	110.87	117.80
0.510	0.179	0.787	48.81	55.78	62.75	69.72	76.70	83.67	90.64	97.61	104.59	111.56	118.53
0.515	0.181	0.788	49.11	56.12	63.14	70.15	77.17	84.19	91.20	98.22	105.23	112.25	119.26
0.520	0.183	0.789	49.41	56.47	63.53	70.59	77.65	84.70	91.76	98.82	105.88	112.94	120.00
0.525	0.184	0.790	49.72	56.82	63.92	71.02	78.12	85.23	92.33	99.43	106.53	113.63	120.74
0.530	0.186	0.791	50.02	57.17	64.31	71.46	78.60	85.75	92.90	100.04	107.19	114.33	121.48
0.535	0.188	0.792	50.33	57.52	64.71	71.90	79.09	86.28	93.47	100.66	107.84	115.03	122.22
0.540	0.190	0.793	50.64	57.87	65.10	72.34	79.57	86.80	94.04	101.27	108.51	115.74	122.97
0.545	0.191	0.795	50.95	58.22	65.50	72.78	80.06	87.33	94.61	101.89	109.17	116.45	123.72
0.550	0.193	0.796	51.26	58.58	65.90	73.22	80.55	87.87	95.19	102.51	109.83	117.16	124.48
0.555	0.195	0.797	51.57	58.94	66.30	73.67	81.04	88.40	95.77	103.14	110.50	117.87	125.24
0.560	0.197	0.798	51.88	59.29	66.71	74.12	81.53	88.94	96.35	103.76	111.18	118.59	126.00
0.565	0.198	0.800	52.20	59.65	67.11	74.57	82.02	89.48	96.94	104.39	111.85	119.31	126.76
0.570	0.200	0.801	52.51	60.02	67.52	75.02	82.52	90.02	97.53	105.03	112.53	120.03	127.53
0.575	0.202	0.802	52.83	60.38	67.93	75.47	83.02	90.57	98.12	105.66	113.21	120.76	128.31
0.580	0.204	0.804	53.15	60.74	68.34	75.93	83.52	91.12	98.71	106.30	113.90	121.49	129.08
0.585	0.205	0.805	53.47	61.11	68.75	76.39	84.03	91.67	99.31	106.94	114.58	122.22	129.86
0.590	0.207	0.806	53.79	61.48	69.16	76.85	84.53	92.22	99.90	107.59	115.27	122.96	130.64
0.595	0.209	0.808	54.12	61.85	69.58	77.31	85.04	92.77	100.51	108.24	115.97	123.70	131.43
0.600	0.211	0.809	54.44	62.22	70.00	77.78	85.55	93.33	101.11	108.89	116.67	124.44	132.22
0.605	0.212	0.811	54.77	62.60	70.42	78.24	86.07	93.89	101.72	109.54	117.37	125.19	133.02
0.610	0.214	0.812	55.10	62.97	70.84	78.71	86.59	94.46	102.33	110.20	118.07	125.94	133.81
0.615	0.216	0.814	55.43	63.35	71.27	79.19	87.11	95.02	102.94	110.86	118.78	126.70	134.62
0.620	0.218	0.815	55.76	63.73	71.70	79.66	87.63	95.59	103.56	111.53	119.49	127.46	135.43
0.625	0.219	0.817	56.10	64.11	72.13	80.14	88.15	96.17	104.18	112.20	120.21	128.22	136.24
0.630	0.221	0.819	56.43	64.50	72.56	80.62	88.68	96.74	104.81	112.87	120.93	128.99	137.05
0.635	0.223	0.820	56.77	64.88	72.99	81.10	89.21	97.32	105.43	113.54	121.65	129.76	137.87
0.640	0.225	0.822	57.11	65.27	73.43	81.59	89.75	97.91	106.06	114.22	122.38	130.54	138.70
0.645	0.226	0.824	57.45	65.66	73.87	82.08	90.28	98.49	106.70	114.91	123.12	131.32	139.53
0.650	0.228	0.825	57.80	66.05	74.31	82.57	90.83	99.08	107.34	115.60	123.85	132.11	140.37
0.655	0.230	0.827	58.14	66.45	74.76	83.06	91.37	99.68	107.98	116.29	124.59	132.90	141.21
0.660	0.232	0.829	58.49	66.85	75.20	83.56	91.92	100.27	108.63	116.99	125.34	133.70	142.05
0.665	0.233	0.831	58.84	67.25	75.66	84.06	92.47	100.87	109.28	117.69	126.09	134.50	142.91
0.670	0.235	0.833	59.20	67.65	76.11	84.57	93.02	101.48	109.94	118.39	126.85	135.31	143.76
0.675	0.237	0.835	59.55	68.06	76.57	85.07	93.58	102.09	110.60	119.10	127.61	136.12	144.63
0.680	0.239	0.837	59.91	68.47	77.03	85.59	94.14	102.70	111.26	119.82	128.38	136.94	145.49
0.685	0.240	0.838	60.27	68.88	77.49	86.10	94.71	103.32	111.93	120.54	129.15	137.76	146.37
0.690	0.242	0.840	60.63	69.29	77.96	86.62	95.28	103.94	112.60	121.27	129.93	138.59	147.25
0.695	0.244	0.842	61.00	69.71	78.43	87.14	95.86	104.57	113.28	122.00	130.71	139.43	148.14
0.700	0.246	0.845	61.37	70.13	78.90	87.67	96.43	105.20	113.97	122.73	131.50	140.27	149.03
0.705	0.247	0.847	61.74	70.56	79.38	88.20	97.02	105.84	114.66	123.48	132.30	141.12	149.94
0.710	0.249	0.849	62.11	70.99	79.86	88.73	97.61	106.48	115.35	124.23	133.10	141.97	150.84
0.715	0.251	0.851	62.49	71.42	80.34	89.27	98.20	107.13	116.05	124.98	133.91	142.83	151.76
0.720	0.253	0.853	62.87	71.85	80.83	89.81	98.80	107.78	116.76	125.74	134.72	143.70	152.68
0.725	0.255	0.855	63.25	72.29	81.33	90.36	99.40	108.43	117.47	126.51	135.54	144.58	153.62
0.730	0.256	0.858	63.64	72.73	81.82	90.91	100.01	109.10	118.19	127.28	136.37	145.46	154.55
0.735	0.258	0.860	64.03	73.18	82.32	91.47	100.62	109.77	118.91	128.06	137.21	146.35	155.50
0.740	0.260	0.862	64.42	73.63	82.83	92.03	101.24	110.44	119.64	128.85	138.05	147.25	156.46
0.745	0.262	0.865	64.82	74.08	83.34	92.60	101.86	111.12	120.38	129.64	138.90	148.16	157.42
0.750	0.263	0.867	65.22	74.54	83.86	93.17	102.49	111.81	121.12	130.44	139.76	149.08	158.39
0.755	0.265	0.870	65.62	75.00	84.37	93.75	103.12	112.50	121.87	131.25	140.62	150.00	159.37
0.760	0.267	0.872	66.03	75.47	84.90	94.33	103.77	113.20	122.63	132.07	141.50	150.93	160.37
0.765	0.269	0.875	66.44	75.94	85.43	94.92	104.41	113.91	123.40	132.89	142.38	151.87	161.37
0.770	0.270	0.877	66.86	76.41	85.96	95.52	105.07	114.62	124.17	133.72	143.27	152.82	162.38
0.775	0.272	0.880	67.28	76.89	86.50	96.12	105.73	115.34	124.95	134.56	144.17	153.78	163.40
0.780	0.274	0.883	67.70	77.38	87.05	96.72	106.39	116.07	125.74	135.41	145.08	154.75	164.43
0.785	0.276	0.885	68.13	77.87	87.60	97.33	107.07	116.80	126.53	136.27	146.00	155.73	165.47
0.790	0.277	0.888	68.57	78.36	88.16	97.95	107.75	117.54	127.34	137.13	146.93	156.72	166.52
0.795	0.279	0.891	69.00	78.86	88.72	98.58	108.43	118.29	128.15	138.01	147.87	157.72	167.58
0.800	0.281	0.894	69.45	79.37	89.29	99.21	109.13	119.05	128.97	138.89	148.81	158.73	168.65
0.805	0.283	0.897	69.89	79.88	89.86	99.85	109.83	119.82	129.80	139.79	149.77	159.75	169.74
0.810	0.284	0.900	70.34	80.39	90.44	100.49	110.54	120.59	130.64	140.69	150.74	160.79	170.84
0.815	0.286	0.903	70.80	80.92	91.03	101.14	111.26	121.37	131.49	141.60	151.72	161.83	171.95
0.820	0.288	0.906	71.26	81.44	91.62	101.80	111.98	122.16	132.35	142.53	152.71	162.89	173.07
0.825	0.290	0.909	71.73	81.98	92.22	102.47	112.72	122.97	133.21	143.46	153.71	163.95	174.20
0.830	0.291	0.913	72.20	82.52	92.83	103.15	113.46	123.77	134.09	144.40	154.72	165.03	175.35
0.835	0.293	0.916	72.68	83.06	93.45	103.83	114.21	124.59	134.98	145.36	155.74	166.13	176.51
0.840	0.295	0.919	73.16	83.62	94.07	104.52	114.97	125.42	135.87				

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

a (in)	a/d (d=2.8486")	F(a/d)	$K_1 = F(a/d)\sigma_v n a$ (ksi/in), where $F(a/d) = 2.043\exp(-31.332a/d) + 0.6507 + 0.5367(a/d) + 3.0469(a/d)^2 - 19.504(a/d)^3 + 45.647(a/d)^4$										
			$\sigma = 0.35F_u$ (49 ksi)	$\sigma = 0.4F_u$ (56 ksi)	$\sigma = 0.45F_u$ (63 ksi)	$\sigma = 0.5F_u$ (70 ksi)	$\sigma = 0.55F_u$ (77 ksi)	$\sigma = 0.6F_u$ (84 ksi)	$\sigma = 0.65F_u$ (91 ksi)	$\sigma = 0.7F_u$ (98 ksi)	$\sigma = 0.75F_u$ (105 ksi)	$\sigma = 0.8F_u$ (112 ksi)	$\sigma = 0.85F_u$ (119 ksi)
0.450	0.158	0.778	45.30	51.77	58.24	64.71	71.19	77.66	84.13	90.60	97.07	103.54	110.01
0.455	0.160	0.778	45.58	52.10	58.61	65.12	71.63	78.14	84.66	91.17	97.68	104.19	110.70
0.460	0.161	0.779	45.87	52.42	58.97	65.53	72.08	78.63	85.19	91.74	98.29	104.84	111.40
0.465	0.163	0.779	46.16	52.75	59.34	65.94	72.53	79.12	85.72	92.31	98.91	105.50	112.09
0.470	0.165	0.780	46.44	53.08	59.71	66.35	72.98	79.62	86.25	92.89	99.52	106.16	112.79
0.475	0.167	0.781	46.73	53.41	60.09	66.76	73.44	80.12	86.79	93.47	100.15	106.82	113.50
0.480	0.169	0.782	47.03	53.74	60.46	67.18	73.90	80.62	87.34	94.05	100.77	107.49	114.21
0.485	0.170	0.782	47.32	54.08	60.84	67.60	74.36	81.12	87.88	94.64	101.40	108.16	114.92
0.490	0.172	0.783	47.61	54.42	61.22	68.02	74.82	81.62	88.43	95.23	102.03	108.83	115.63
0.495	0.174	0.784	47.91	54.75	61.60	68.44	75.29	82.13	88.98	95.82	102.67	109.51	116.35
0.500	0.176	0.785	48.21	55.09	61.98	68.87	75.76	82.64	89.53	96.42	103.30	110.19	117.08
0.505	0.177	0.786	48.51	55.44	62.37	69.30	76.22	83.15	90.08	97.01	103.94	110.87	117.80
0.510	0.179	0.787	48.81	55.78	62.75	69.72	76.70	83.67	90.64	97.61	104.59	111.56	118.53
0.515	0.181	0.788	49.11	56.12	63.14	70.15	77.17	84.19	91.20	98.22	105.23	112.25	119.26
0.520	0.183	0.789	49.41	56.47	63.53	70.59	77.65	84.70	91.76	98.82	105.88	112.94	120.00
0.525	0.184	0.790	49.72	56.82	63.92	71.02	78.12	85.23	92.33	99.43	106.53	113.63	120.74
0.530	0.186	0.791	50.02	57.17	64.31	71.46	78.60	85.75	92.90	100.04	107.19	114.33	121.48
0.535	0.188	0.792	50.33	57.52	64.71	71.90	79.09	86.28	93.47	100.66	107.84	115.03	122.22
0.540	0.190	0.793	50.64	57.87	65.10	72.34	79.57	86.80	94.04	101.27	108.51	115.74	122.97
0.545	0.191	0.795	50.95	58.22	65.50	72.78	80.06	87.33	94.61	101.89	109.17	116.45	123.72
0.550	0.193	0.796	51.26	58.58	65.90	73.22	80.55	87.87	95.19	102.51	109.83	117.16	124.48
0.555	0.195	0.797	51.57	58.94	66.30	73.67	81.04	88.40	95.77	103.14	110.50	117.87	125.24
0.560	0.197	0.798	51.88	59.29	66.71	74.12	81.53	88.94	96.35	103.76	111.18	118.59	126.00
0.565	0.198	0.800	52.20	59.65	67.11	74.57	82.02	89.48	96.94	104.39	111.85	119.31	126.76
0.570	0.200	0.801	52.51	60.02	67.52	75.02	82.52	90.02	97.53	105.03	112.53	120.03	127.53
0.575	0.202	0.802	52.83	60.38	67.93	75.47	83.02	90.57	98.12	105.66	113.21	120.76	128.31
0.580	0.204	0.804	53.15	60.74	68.34	75.93	83.52	91.12	98.71	106.30	113.90	121.49	129.08
0.585	0.205	0.805	53.47	61.11	68.75	76.39	84.03	91.67	99.31	106.94	114.58	122.22	129.86
0.590	0.207	0.806	53.79	61.48	69.16	76.85	84.53	92.22	99.90	107.59	115.27	122.96	130.64
0.595	0.209	0.808	54.12	61.85	69.58	77.31	85.04	92.77	100.51	108.24	115.97	123.70	131.43
0.600	0.211	0.809	54.44	62.22	70.00	77.78	85.55	93.33	101.11	108.89	116.67	124.44	132.22
0.605	0.212	0.811	54.77	62.60	70.42	78.24	86.07	93.89	101.72	109.54	117.37	125.19	133.02
0.610	0.214	0.812	55.10	62.97	70.84	78.71	86.59	94.46	102.33	110.20	118.07	125.94	133.81
0.615	0.216	0.814	55.43	63.35	71.27	79.19	87.11	95.02	102.94	110.86	118.78	126.70	134.62
0.620	0.218	0.815	55.76	63.73	71.70	79.66	87.63	95.59	103.56	111.53	119.49	127.46	135.43
0.625	0.219	0.817	56.10	64.11	72.13	80.14	88.15	96.17	104.18	112.20	120.21	128.22	136.24
0.630	0.221	0.819	56.43	64.50	72.56	80.62	88.68	96.74	104.81	112.87	120.93	128.99	137.05
0.635	0.223	0.820	56.77	64.88	72.99	81.10	89.21	97.32	105.43	113.54	121.65	129.76	137.87
0.640	0.225	0.822	57.11	65.27	73.43	81.59	89.75	97.91	106.06	114.22	122.38	130.54	138.70
0.645	0.226	0.824	57.45	65.66	73.87	82.08	90.28	98.49	106.70	114.91	123.12	131.32	139.53
0.650	0.228	0.825	57.80	66.05	74.31	82.57	90.83	99.08	107.34	115.60	123.85	132.11	140.37
0.655	0.230	0.827	58.14	66.45	74.76	83.06	91.37	99.68	107.98	116.29	124.59	132.90	141.21
0.660	0.232	0.829	58.49	66.85	75.20	83.56	91.92	100.27	108.63	116.99	125.34	133.70	142.05
0.665	0.233	0.831	58.84	67.25	75.66	84.06	92.47	100.87	109.28	117.69	126.09	134.50	142.91
0.670	0.235	0.833	59.20	67.65	76.11	84.57	93.02	101.48	109.94	118.39	126.85	135.31	143.76
0.675	0.237	0.835	59.55	68.06	76.57	85.07	93.58	102.09	110.60	119.10	127.61	136.12	144.63
0.680	0.239	0.837	59.91	68.47	77.03	85.59	94.14	102.70	111.26	119.82	128.38	136.94	145.49
0.685	0.240	0.838	60.27	68.88	77.49	86.10	94.71	103.32	111.93	120.54	129.15	137.76	146.37
0.690	0.242	0.840	60.63	69.29	77.96	86.62	95.28	103.94	112.60	121.27	129.93	138.59	147.25
0.695	0.244	0.842	61.00	69.71	78.43	87.14	95.86	104.57	113.28	122.00	130.71	139.43	148.14
0.700	0.246	0.845	61.37	70.13	78.90	87.67	96.43	105.20	113.97	122.73	131.50	140.27	149.03
0.705	0.247	0.847	61.74	70.56	79.38	88.20	97.02	105.84	114.66	123.48	132.30	141.12	149.94
0.710	0.249	0.849	62.11	70.99	79.86	88.73	97.61	106.48	115.35	124.23	133.10	141.97	150.84
0.715	0.251	0.851	62.49	71.42	80.34	89.27	98.20	107.13	116.05	124.98	133.91	142.83	151.76
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0.800	0.281	0.894	69.45	79.37	89.29	99.21	109.13	119.05	128.97	138.89	148.81	158.73	168.65
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0.810	0.284	0.900	70.34	80.39	90.44	100.49	110.54	120.59	130.64	140.69	150.74	160.79	170.84
0.815	0.286	0.903	70.80	80.92	91.03	101.14	111.26	121.37	131.49	141.60	151.72	161.83	171.95
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0.840	0.295	0.919	73.16	83.62	94.07	104.52	114.97	125.42	135.87				

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

a (in)	a/d (d=2.8486")	F(a/d)	$K_1 = F(a/d)\sigma_v n a$ (ksi·in), where $F(a/d) = 2.043\exp(-31.332a/d) + 0.6507 + 0.5367(a/d) + 3.0469(a/d)^2 - 19.504(a/d)^3 + 45.647(a/d)^4$										
			$\sigma = 0.35F_u$ (49 ksi)	$\sigma = 0.4F_u$ (56 ksi)	$\sigma = 0.45F_u$ (63 ksi)	$\sigma = 0.5F_u$ (70 ksi)	$\sigma = 0.55F_u$ (77 ksi)	$\sigma = 0.6F_u$ (84 ksi)	$\sigma = 0.65F_u$ (91 ksi)	$\sigma = 0.7F_u$ (98 ksi)	$\sigma = 0.75F_u$ (105 ksi)	$\sigma = 0.8F_u$ (112 ksi)	$\sigma = 0.85F_u$ (119 ksi)
0.080	0.028	1.515	37.22	42.54	47.86	53.17	58.49	63.81	69.13	74.44	79.76	85.08	90.40
0.082	0.029	1.497	37.24	42.56	47.88	53.20	58.52	63.84	69.15	74.47	79.79	85.11	90.43
0.084	0.029	1.480	37.25	42.57	47.89	53.21	58.53	63.85	69.17	74.49	79.81	85.13	90.46
0.086	0.030	1.463	37.25	42.57	47.89	53.21	58.54	63.86	69.18	74.50	79.82	85.14	90.46
0.088	0.031	1.446	37.25	42.57	47.89	53.21	58.53	63.85	69.17	74.50	79.82	85.14	90.46
0.090	0.032	1.429	37.24	42.56	47.88	53.20	58.52	63.84	69.16	74.48	79.80	85.12	90.44
0.092	0.032	1.413	37.23	42.55	47.87	53.19	58.50	63.82	69.14	74.46	79.78	85.10	90.42
0.094	0.033	1.398	37.21	42.53	47.85	53.16	58.48	63.80	69.11	74.43	79.75	85.06	90.38
0.096	0.034	1.382	37.20	42.51	47.82	53.14	58.45	63.76	69.08	74.39	79.71	85.02	90.33
0.098	0.034	1.367	37.17	42.48	47.80	53.11	58.42	63.73	69.04	74.35	79.66	84.97	90.28
0.100	0.035	1.353	37.15	42.46	47.76	53.07	58.38	63.68	68.99	74.30	79.61	84.91	90.22
0.105	0.037	1.317	37.08	42.37	47.67	52.97	58.26	63.56	68.86	74.15	79.45	84.75	90.04
0.110	0.039	1.284	36.99	42.28	47.56	52.85	58.13	63.41	68.70	73.98	79.27	84.55	89.84
0.115	0.040	1.253	36.90	42.17	47.44	52.71	57.98	63.26	68.53	73.80	79.07	84.34	89.61
0.120	0.042	1.223	36.80	42.06	47.32	52.57	57.83	63.09	68.35	73.60	78.86	84.12	89.38
0.125	0.044	1.195	36.70	41.94	47.19	52.43	57.67	62.92	68.16	73.40	78.65	83.89	89.13
0.130	0.046	1.169	36.60	41.83	47.06	52.29	57.52	62.75	67.97	73.20	78.43	83.66	88.89
0.135	0.047	1.144	36.50	41.72	46.93	52.15	57.36	62.58	67.79	73.01	78.22	83.44	88.65
0.140	0.049	1.120	36.41	41.61	46.81	52.01	57.22	62.42	67.62	72.82	78.02	83.22	88.42
0.145	0.051	1.098	36.32	41.51	46.70	51.89	57.08	62.26	67.45	72.64	77.83	83.02	88.21
0.150	0.053	1.077	36.24	41.41	46.59	51.77	56.95	62.12	67.30	72.48	77.65	82.83	88.01
0.155	0.054	1.058	36.16	41.33	46.49	51.66	56.83	61.99	67.16	72.32	77.49	82.66	87.82
0.160	0.056	1.039	36.09	41.25	46.41	51.56	56.72	61.88	67.03	72.19	77.35	82.50	87.66
0.165	0.058	1.021	36.04	41.18	46.33	51.48	56.63	61.78	66.92	72.07	77.22	82.37	87.52
0.170	0.060	1.005	35.99	41.13	46.27	51.41	56.55	61.69	66.83	71.97	77.11	82.25	87.39
0.175	0.061	0.989	35.95	41.08	46.22	51.35	56.49	61.62	66.76	71.89	77.03	82.16	87.30
0.180	0.063	0.975	35.92	41.05	46.18	51.31	56.44	61.57	66.70	71.83	76.96	82.09	87.22
0.185	0.065	0.961	35.90	41.02	46.15	51.28	56.41	61.53	66.66	71.79	76.92	82.05	87.17
0.190	0.067	0.948	35.88	41.01	46.14	51.26	56.39	61.52	66.64	71.77	76.90	82.02	87.15
0.195	0.068	0.936	35.89	41.01	46.14	51.26	56.39	61.52	66.64	71.77	76.90	82.02	87.15
0.200	0.070	0.924	35.90	41.02	46.15	51.28	56.41	61.53	66.66	71.79	76.92	82.05	87.17
0.205	0.072	0.913	35.92	41.05	46.18	51.31	56.44	61.57	66.70	71.83	76.96	82.09	87.22
0.210	0.074	0.903	35.95	41.08	46.22	51.35	56.49	61.62	66.76	71.89	77.03	82.16	87.30
0.215	0.075	0.894	35.99	41.13	46.27	51.41	56.55	61.69	66.83	71.97	77.12	82.26	87.40
0.220	0.077	0.885	36.04	41.19	46.33	51.48	56.63	61.78	66.93	72.08	77.22	82.37	87.52
0.225	0.079	0.876	36.10	41.26	46.41	51.57	56.73	61.88	67.04	72.20	77.35	82.51	87.67
0.230	0.081	0.868	36.17	41.34	46.50	51.67	56.84	62.00	67.17	72.34	77.50	82.67	87.84
0.235	0.082	0.861	36.25	41.43	46.60	51.78	56.96	62.14	67.32	72.50	77.67	82.85	88.03
0.240	0.084	0.854	36.34	41.53	46.72	51.91	57.10	62.29	67.48	72.67	77.86	83.05	88.24
0.245	0.086	0.848	36.43	41.64	46.84	52.05	57.25	62.46	67.66	72.87	78.07	83.28	88.48
0.250	0.088	0.841	36.54	41.76	46.98	52.20	57.42	62.64	67.86	73.08	78.30	83.52	88.74
0.255	0.090	0.836	36.65	41.89	47.13	52.36	57.60	62.83	68.07	73.31	78.54	83.78	89.02
0.260	0.091	0.830	36.78	42.03	47.28	52.54	57.79	63.04	68.30	73.55	78.81	84.06	89.31
0.265	0.093	0.825	36.91	42.18	47.45	52.72	58.00	63.27	68.54	73.81	79.08	84.36	89.63
0.270	0.095	0.821	37.04	42.34	47.63	52.92	58.21	63.50	68.80	74.09	79.38	84.67	89.96
0.275	0.097	0.817	37.19	42.50	47.82	53.13	58.44	63.75	69.07	74.38	79.69	85.00	90.32
0.280	0.098	0.813	37.34	42.68	48.01	53.35	58.68	64.02	69.35	74.68	80.02	85.35	90.69
0.285	0.100	0.809	37.50	42.86	48.22	53.57	58.93	64.29	69.65	75.00	80.36	85.72	91.08
0.290	0.102	0.805	37.67	43.05	48.43	53.81	59.19	64.57	69.95	75.34	80.72	86.10	91.48
0.295	0.104	0.802	37.84	43.25	48.65	54.06	59.46	64.87	70.27	75.68	81.09	86.49	91.90
0.300	0.105	0.799	38.02	43.45	48.88	54.31	59.74	65.18	70.61	76.04	81.47	86.90	92.33
0.305	0.107	0.796	38.20	43.66	49.12	54.58	60.03	65.49	70.95	76.41	81.86	87.32	92.78
0.310	0.109	0.794	38.39	43.88	49.36	54.85	60.33	65.82	71.30	76.79	82.27	87.76	93.24
0.315	0.111	0.792	38.59	44.10	49.62	55.13	60.64	66.15	71.67	77.18	82.69	88.20	93.72
0.320	0.112	0.790	38.79	44.33	49.87	55.42	60.96	66.50	72.04	77.58	83.12	88.66	94.21
0.325	0.114	0.788	39.00	44.57	50.14	55.71	61.28	66.85	72.42	77.99	83.56	89.14	94.71
0.330	0.116	0.786	39.21	44.81	50.41	56.01	61.61	67.21	72.81	78.41	84.02	89.62	95.22
0.335	0.118	0.784	39.42	45.05	50.69	56.32	61.95	67.58	73.21	78.85	84.48	90.11	95.74
0.340	0.119	0.783	39.64	45.31	50.97	56.63	62.30	67.96	73.62	79.29	84.95	90.61	96.28
0.345	0.121	0.782	39.87	45.56	51.26	56.95	62.65	68.34	74.04	79.73	85.43	91.13	96.82
0.350	0.123	0.780	40.10	45.82	51.55	57.28	63.01	68.74	74.46	80.19	85.92	91.65	97.38
0.355	0.125	0.779	40.33	46.09	51.85	57.61	63.37	69.13	74.89	80.66	86.42	92.18	97.94
0.360	0.126	0.778	40.56	46.36	52.15	57.95	63.74	69.54	75.33	81.13	86.92	92.72	98.51
0.365	0.128	0.778	40.80	46.63	52.46	58.29	64.12	69.95	75.78	81.61	87.44	93.26	99.09
0.370	0.130	0.777	41.05	46.91	52.77	58.64	64.50	70.37	76.23	82.09	87.96	93.82	99.68
0.375	0.132	0.776	41.29	47.19	53.09	58.99	64.89	70.79	76.69	82.59	88.48	94.38	100.28
0.380	0.133	0.776	41.54	47.48	53.41	59.35	65.28	71.22	77.15	83.08	89.02	94.95	100.89
0.385	0.135	0.776	41.79	47.77	53.74	59.71	65.68	71.65	77.62	83.59	89.56	95.53	101.50
0.390	0.137	0.775	42.05	48.06	54.06	60.07	66.08	72.09	78.09	84.10	90.11	96.11	102.12
0.395	0.139	0.775	42.31	48.35	54.40	60.44	66.48	72.53	78.57	84.62	90.66	96.70	102.75
0.400	0.140	0.775	42.57	48.65	54.73	60.81	66.89	72.97	79.06	85.14	91.22	97.30	103.38
0.405	0.142	0.775	42.83	48.95	55.07	61.19	67.31	73.43	79.55	85.66	91.78	97.90	104.02
0.410	0.144	0.775	43.10	49.25	55.41	61.57	67.72	73.88	80.04	86.20	92.35	98.51	104.67
0.415	0.146	0.775	43.37	49.56	55.76	61.95	68.15	74.34	80.54	86.73	92.93	99.12	105.32
0.420	0.147	0.775	43.64	49.87	56.10	62.34	68.57	74.80	81.04	87.27	93.51	99.74	105.97
0.425	0.149	0.775	43.91	50.18	56.45	62.73	69.00	75.27	81.54	87.82	94.09	100.36	106.63
0.430	0.151	0.776	44.18	50.49	56.81	63.12	69.43	75.74	82.05	88.37	94.68	100.99	107.30
0.435	0.153	0.776	44.46	50.81	57.16	63.51	69.86	76.22	82.57	88.92	95.27	101.62	107.97
0.440	0.154	0.777	44.74	51.13	57.52	63.91	70.30	76.69	83.08	89.48	95.87	102.26	108.65
0.445	0.156	0.777	45.02	51.45	57.88	64.31	70.74	77.17	83.60	90.04	96.47	102.90	109.33
0.450	0.158	0.778	45.30	51.77	58.24	64.71	71.19	77.66	84.13	90.60	97.07	103.54	110.01

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SCC of HCB Bolts – Field Investigation

During the BAMC July 16th visit to the HCB, the location and extent of the galvanized coating on all 3 inch bolts was investigated. It was found that above the nuts in the non-stressed portion of the bolts – and therefore areas that would not be susceptible to SCC - that there was a seemingly random pattern of galvanized and non-galvanized bolt surfaces. However, galvanizing was consistently found on the stressed portion of all the bolts on the bolt threads and shaft under the top nut.

Corrosion was found on two of the bolts – 7WS and 7EN - under the nut at the root of the threaded stressed portion of the bolts where susceptibility to SCC would be the greatest. The corrosion on Bolt 7WS appeared to be more critical. It is not known how long this corrosion has been active. Bolt 7WS had a flat end at the bottom of the bolt, indicating that it was a replacement bolt from the Lofall Storage Facility, and most probably from the original lot from Dyson/Thompson Metal Fab. Given the very low toughness of these bolts they would have a high probability of susceptibility to SCC. The origin of bolt 7EN is not known at time of writing.

There could be SCC problems for these bolts in the future but at this time the only way to ascertain if there is a long term concern for SCC would be to allow them to further corrode. However, WSDOT Maintenance does intend to clean and paint these bolts, and to bolster their painting program for all bolts going forward.



Corrosion at Galvanized Stressed Top Threads of Bolt 7WS

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Corrosion at Galvanized Stressed Top Threads of Bolt 7EN

At the East Half of the HCB, the existing 16- 4 inch and the 12-3 inch ASTM A354 BD bolts have been in service since June of 2009 or 4 ½ years at time of writing. As discussed, all 12 of the original 3 inch bolts have been replaced, 6 of alloy AISI 4340 and most probably 6 of alloy AISI 4140 from the original 2004 Dyson lot. Eight of the 4 inch bolts are from the original 2004 Dyson lot with material properties very similar to the 3 inch bolts. The origin of the other 8 - 4 inch bolts is not known.

As 6 of the (3 inch) 2004 bolts have failed due to HE and 14 of the bolts are thought to be of the same lot with identical or similar material properties (6 – 3 inch and 8 – 4 inch), it would appear that there would be concern that these bolts would be susceptible to SCC. However, there have been no noted problems with these bolts since their installation, i.e. none have failed by SCC, and none have shown any indications of cracks.

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Why have there been no problems with replacement bolts to date?

As discussed previously, there are measures that can be taken to control or lessen susceptibility to SCC, and WSDOT has taken a number of these measures for the East Half A354 BD bolts:

- Exposed portions of all the bolts are painted.
- The portions of all the bolts embedded in the pontoon wall are contained in grease filled ducts.
- The bolt threads at the bottom of the bolt are protected by grease in the duct and the top threads at the nut are protected by high pressure silicone, rust inhibiting, waterproof grease that was specified to be applied to the threads prior to tensioning. It was verified by spot checks during BAMC visits in June and July 2013 that grease was present in the ducts and at the most critical first engaged thread at the bottom of the top nut.
- Grease and paint were applied soon after bolt installation and stressing.
- The pretension of the 4 inch bolts was limited to 0.53 Fu.
- The 3 inch bolts were pretensioned to 0.70 Fu but the potential for non-concentric loading was eliminated by the 2 inch thick replacement washers.
- AISI 4340 alloy was specified for 6 of the 3 inch replacement bolts. These exhibited uniform hardness and high toughness with an avg. Charpy value at -20 F of 46 ft-lbs.
- All the 4 inch bolts and 6 of the 3 inch AISI 4140 bolts have rolled threads rather than cut threads making them less susceptible to SCC. (The AISI 4340 bolts have cut threads.)

VI. Summary - Guide Roller Box Girder HS Anchor Bolts

East Half	Spec ASTM	Dia in	Alloy AISI	Supplier	Install Year	Length ft	Coating	Min Fu ksi	Min Fy ksi	Pretension	Threads
8-Original	A354 BD	4	4140	DYSON	2009	21	Galvanized	140	115	0.53 Fu	Rolled
8-Original	A354 BD	4	UNK	DYSON	2009	21	Galvanized	140	115	0.53Fu	Rolled
2-Replace	A354 BD	4	UNK	DYSON	2009	21	Galvanized	140	115	0.53Fu	Rolled
12-Original	A354 BD	3	4140	DYSON	2009	21	Galvanized	140	115	0.70Fu	Rolled
6-Replace	A354 BD	3	4140	DYSON	2009	21	Galvanized	140	115	0.70Fu	Rolled
6-Replace	A354 BD	3	4340	Portland Bolt	2009	21	Galvanized	140	115	0.70Fu	Cut
28-Original	A345 BC	1 ½	UNK	UNK	2009	6	Galvanized	115	99	Snug Tight	UNK
West Half	SPEC ASTM	Dia in	Alloy AISI	Supplier	Install Year	Length ft	Coating	Min Fu ksi	Min Fy ksi	Pretension	Threads
16-Original	A354 BD	4	UNK	UNK	1982	21	none	140	115	0.53 Fu	UNK
12-Original	A354 BD	3	UNK	UNK	1982	21	none	140	115	0.78 Fu	UNK
28-Original	A325	1 ½	UNK	UNK	1982	6	none	105	81	Snug Tight	UNK

All Box Girder Anchor Bolts are:

- Encased in a galvanized steel pipe and pressure filled with grease after stressing the bolt.
- Painted with the standard WSDOT 3 coat paint system on exposed portions of bolt.
- Subjected to yearly visual and NDT inspection.

VII. Transition Span A-Frame Anchor Bolts

The A-frames that support the transition span are anchored to the pontoon with 2 inch diameter, 8 ft. long F1554 HS bolts. The bolts are tensioned to 0.6 Fy and the duct is grouted after tensioning. At time of writing the corrosion protective coating, if any other than painting, is not known.



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VIII. Centering Pyramid Anchor Bolts

The two 6' high by 4' wide centering pyramids located at mid-channel on the east draw pontoon with mating yokes on the west pontoon are anchored to the pontoon with 7.5 ft. long 1 ½ and 1 ¾ inch F1554 Grade 105 anchor bolts. The bolts are tensioned to 0.6 Fy and the duct is grouted after tensioning. The bolts are galvanized and the exposed portion of the bolt and nut are treated with inorganic zinc paint.



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Appendix A

Report of 6/28/2013 Visit to Hood Canal Bridge and to Dwight Company

Purpose of Visit

Discuss Hood Canal Bridge (HCB) experience with galvanized ASTM A354 Grade BD anchor rods and determine if the experience with those rods provides information useful in evaluating the causes and possible remedies of the failures experienced with 2008 anchor rods at the San Francisco Oakland Bay Bridge (SFOBB).

Locations Visited

- 1) Hood Canal Bridge, SR 104, Kitsap Co., in the Puget Sound region of the State of Washington
- 2) Dwight Company Inc. Welding Laboratory Service, 414 Hewitt Road, Chehalis, WA 98532

Persons Making Visit

Alan Cavendish-Tribe, Mott MacDonald
Jeff Gorman, Dominion Engineering, Inc.
Ted Hall, Hatch Mott MacDonald
Robert Shulock, Bainbridge Structures Group

Persons contacted

Paul Knaebel, Maintenance Engineer, Hood Canal Bridge, Washington State Department of Transportation (WSDOT)
Jay Dwight, Proprietor, Dwight Company Inc. Welding Laboratory Service, Chehalis, WA

Summary

Several 3 inch diameter anchor rods in the new east pontoons of the HCB failed shortly after being tensioned in 2008. These rods had been hot dip galvanized for their full length. Based on optical microscopy, the failure morphology of these rods appears similar to that of the San Francisco Oakland Bay Bridge (SFOBB) rods that failed in March 2013. However, this needs to be confirmed by examination using a scanning electron microscope (SEM) before one can conclude that the failure mechanism is in fact the same.

Hardness checks performed during the visit by Jay Dwight on samples of the failed HCB rods from 2008 indicated that the rods had a rather flat hardness profile across the cross section, with maximum hardness of 32.5 HRC and with decreases to only about HRC 30 at depths of 0.75 inches. These results raise a question as to why failure occurred with material that had hardness well below the specification limit of 39 HRC and also well below the value of 35 HRC that is normally considered a safe

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upper limit against occurrence of hydrogen embrittlement. Speculatively, a possible reason is the presence of large amounts of hydrogen in the steel, e.g., as a result of not vacuum degassing the steel during melting. However, it is noted that the Dwight Company report of 2009 concluded that hydrogen embrittlement was not involved [0]. Since this last conclusion was not based on an examination using an SEM, it seems possible or even likely that a more detailed examination will show hydrogen embrittlement to have been involved.

The anchor rods in the new east pontoons, which went into service in 2009, are still in service, with no failures since the rods that failed shortly after tensioning were replaced. In other words, there has been no experience of long term stress corrosion cracking (SCC) of these rods. All but the top 7 inches of these rods were zinc plated and painted with the WSDOT three coat system. The top ends of the rods and the top nuts in this new east pontoon were solvent and blast cleaned prior to being painted. Some of the top ends show significant amounts of general corrosion, but this does not seem to have resulted in any problems other than the need to recoat on a periodic basis. The tension level in the 3 in. diameter rods is believed to be 0.70 Fu, and in the 4 in. diameter rods is believed to be 0.53 Fu. This satisfactory experience of the new east side anchor rods for about four years with no SCC despite the relatively harsh marine environment indicates that galvanized rods with blasted and coated ends are likely to perform satisfactorily for at least four years, and possibly much longer.

The anchor rods on the older west pontoons, which went into service about 32 years ago, were not zinc coated but rather are black and protected with grease in the duct embedded in the pontoon concrete. The exposed portions of the nuts, bolts and washers were painted with the WSDOT three coat paint system. There have been no SCC failures of these rods. The tension level in the 3 in. diameter rods is believed to be 0.70 Fu, and in the 4 in. diameter rods is believed to be 0.53 Fu. The satisfactory experience of the west side rods for 32 years with no SCC despite the relatively harsh marine environment indicates that greased and sheathed designs combined with blasted and painted exposed ends provide good long term protection against corrosion induced SCC.

Recommendations

It is recommended that the failure surfaces and other features of the failed HCB rods be further examined to more conclusively determine if hydrogen embrittlement was involved. In addition to SEM examinations of the fracture surfaces, it would be useful to perform the array of examinations suggested by Prof. Devine for the 2008 SFOBB 2008 failed rods and discussed in Reference [0]. It would also be useful to determine the chemical composition of the steel.

It is recommended that an attempt be made to determine if the steel for the 2008 HCB rods that failed had been vacuum degassed or not. The reason for this recommendation is that it is considered important to determine whether the

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occurrence of hydrogen embrittlement correlates with use of non-degassed steel. If use of non-degassed steel is found to be a significant factor, then use of vacuum degassing should be specified for future anchor rod procurements.

If practical, a more complete description of the corrosion protection situation for the full height of the east and west side anchor rods on the HCB would be useful so that all of the features that appear to have successfully protected against SCC are understood.

Information Obtained Regarding Experience with Anchor Rods Used at the Hood Floating Canal Bridge

Note: Much of this information was developed Bob Shulock via contract documents and his contacts with WSDOT personnel before and after the visit. Additional information was obtained from discussions with Paul Knaebel during the visit.

A document that was prepared by BAMC before the visit describes the HCB and its anchor rods [0]. The anchor rods are used to hold down box girders that support rollers that guide the draw pontoons into the forks on the east and west sides of the bridge. The anchor rods nearest the rollers at the front of the box beam are the most highly loaded. These rods are 20 ft. long, greased and sheathed 3 in. diameter at the less highly loaded guide rollers at the back portion of the fork and 4 in. diameter at the more highly loaded rollers at the front portion of the fork. On the west side both the 3 in. and 4 in. rods are black, not galvanized, A354 BD (4140 alloy). On the east side, the 4 in. diameter rods are galvanized A354 BD bolts (4140 alloy) and the 3 in. diameter rods are galvanized A354 BD bolts (4340 alloy).

The floating pontoons on the east side of the Hood Canal Bridge were replaced in 2008. It is understood that, during final fit-out of the Draw Pontoon System at a shipyard in March 2009, three or more of the 3" diameter anchor rods were found to have failed a few days or weeks after being tensioned. (Note: Time to failure after stressing to be verified by Project Records.) It is further understood that the rods had been supplied by Dyson in 2008, and had been hot dip galvanized. In addition, it is understood that replacements for the failed anchor rods were obtained from Portland Bolt, who declined to galvanize them, and that they were galvanized at another location under a separate contract.

The drawings for the 2008 anchor rods are part of a set of drawings for the box girders [0]. The cover sheet of this set of drawing is dated 10/19/09, but the drawings themselves are dated 7/26/07. The drawing sheet that includes the anchor rods, Thompson Metal Fab. Inc. drawing 03-18010-05, Rev 2, "Pontoon Box Girders Type 1, 2, 3, 4, 5, 6, and 7 – Embeds & Anchor Rods," indicates that the rods and nuts were to be galvanized, but the galvanizing process to be used was not specified.

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A drawing for six replacement rods is shown on Reference [0]. It is titled "SR 104 Hood Canal Bridge Retrofit and East Half Replacement, Box Girder 3 Inch Rods" and appears to be dated 05/09. The drawing indicates that the rods were to be A354BD, and that the material should be Alloy 4340 with a minimum Charpy impact energy of 15 ft-lbs at 20°F. The drawing indicates that all but the top 7 inches of the rods should be hot dip galvanized. It indicates that the top nut and top 7 inches of the threads were not to be galvanized and were to be sand blasted and painted with a three coat system.

During the visit it was determined that none of the three inch or four inch anchor rods on the new east side pontoons had failed since it was put into operation in about 2009. However, it was noted that some of the three inch anchor rods on the east side had significant visible red rust type corrosion on the ends sticking above the nuts. Paul Knaebel indicated that these corroded ends would probably be blasted and recoated with a three layer coating system. It was noted that there was a grease fitting for each of the anchor rods. Paul Knaebel indicated that this had been used during initial construction but had not been used since.

The west side pontoons have been in operation for about 32 years. There have been no failures of its anchor rods. The anchor rods, nuts and washers on the west side were not galvanized. The exposed ends of the rods and the nuts at either end appear to have been painted using the WSDOT standard three coat system. During the visit it was noted that some of the lower nuts exhibited significant accumulations of rust on the lower surface. Visual inspection of a few sections of the rods along their exposed lengths indicated occasional small areas of corrosion.

Information Obtained During Visit to Dwight Company Inc. Welding Laboratory Service

Based on information from WSDOT it was known that portions of two of the 3 inch diameter HCB anchor rods that failed in 2008 had been examined by Jay Dwight as reported in Reference [0]. This report concluded that the failures were not associated with hydrogen embrittlement but rather were due to non-concentric loading during the final torque tensioning. However, the illustrations of the failure surfaces in that report indicate that the failure surface patterns are similar to those for the 2008 failed rods from the SFOBB. During telephone conversations with Jay Dwight prior to the visit it had been learned that the physical parts of the failed HCB rods were still available at the Dwight Company facilities. Accordingly, this visit was arranged with the intent of learning more about the HCB rod failures, and especially to determine if the failures could have been due to hydrogen embrittlement. Information obtained during the visit is described in the following paragraphs.

Detailed examination using high power optical microscopes of the fracture surfaces of the two HCB failed rods indicated that the failure patterns were similar to those of the 2008 SFOBB rods that failed in March 2013. This pattern consists of a flat area extending around about ½ or more of the circumference of the rod and extending in from the edge

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about 1/2 inch at the maximum. The rest of the fracture surface is rough, and seems typical of a surface produced by fast fracture. Since an SEM was not available, it was not possible to examine the flat surfaces to determine if the morphology in those areas was intergranular, which would indicate that hydrogen embrittlement was involved.

The conclusion of the Reference [0] report that the failure was caused by non-concentric loading during the final torque tensioning was discussed. It was agreed that non-concentric loading would cause bending and thus increase stresses. However, it was also noted that the rod material, without hydrogen embrittlement, should be able to strain about 14% or more, and thus should not fail as a result of non-concentric loading, although it might plastically deform a small amount. This topic was not pursued since determining conclusively the failure mechanism requires examination by SEM to determine if the flat areas cracked intergranularly.

During the visit, Jay Dwight took hardness measurements across part of the diameter in a sectioned part of the rods away from the failure surface. The hardness tester was first calibrated, and then measurements were taken. The results were as follows:

Sample Number	Distance in from Thread OD, in.	HRC
#5	.15	30.1
	.25	31
	.3	31.5
	.5	32.5
	.625	32
	.75	31
	#8	.15
.2		31.5
.3		30
.4		31.5
.5		31
.625		30.1
.75		31.1

It was noted that the relatively flat hardness profile appeared to be more consistent with the rods being made of Alloy 4340 than Alloy 4140. However, determining this conclusively would require a chemical analysis of the steel to be performed.

It was noted that the broken rods had been observed in April 2009 but that it was not known at time of writing when the rods had been tensioned.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

Several areas of the failed specimens were examined using high power optical microscopes. Some areas showed the zinc plating and the zinc-steel interface to be extensively cracked. However, it is not known whether this cracking occurred before rod failure or as a consequence of rod failure. In other areas the zinc plating appeared to be intact with no cracks. A more detailed and systematic examination would be required to determine if fractures in the zinc plating or zinc-steel interface played a role in the HCB rod failures.

References

- “High Strength Anchor Bolts, Greased and Sheathed Double Corrosion Protection Systems, Suppliers and Applications - Bridge and Other Industries;” BAMC June 26, 2013.
- Kiewit-General drawing transmittal sheet dated 10/19/09, titled “A05030.22.045.b – Roller Guide Box Girder Show Drawing – AS-BUILT,” with attached Thompson Metal Fab., Inc. drawings 03-18010-00, 01, 02, 04, 05 and 06, Rev. 2, that are dated 7/26/07.
- WSDOT drawing “SR 104 Hood Canal Bridge Retrofit and East Half Replacement, Box Girder 3 Inch Rods,” Job Number DOC 524, designed by G. D. Swett, 05/09.
- J. M. Dwight, “Metallurgical Record of FW 3" Bolt Failures on East Half- 2009,” DWIGHT COMPANY, Inc. WELDING LABORATORY SERVICE report dated April 26, 2009.
- “Professor Thomas Devine Suggestions [1], with Proposed Follow Up Actions,” forwarded to BAMC by email from J. Gorman (DEI) dated July 2, 2013.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

Appendix B

Report of Second Visit to Hood Canal Bridge

Date of Visit: July 16, 2013

Purpose of Visit

Discuss Hood Canal Bridge (HCB) experience with ASTM A354 Grade BD anchor rods and determine if the experience with those rods provides information useful in evaluating corrosion protection measures for anchor rods used in the San Francisco Oakland Bay Bridge (SFOBB).

Location Visited

Hood Canal Bridge, SR 104, Kitsap Co., in the Puget Sound region of the State of Washington

Persons Making Visit

Tony Anziano, Caltrans
Bahjat Dagher, Caltrans (Alta Vista Solutions)
Jeff Gorman, BAMC (Dominion Engineering, Inc.)
Ted Hall, BAMC (Hatch Mott MacDonald)
Robert Shulock, BAMC (Bainbridge Structures Group)
Mazen Wahbeh, Caltrans (Alta Vista Solutions)

Persons contacted

Paul Knaebel, Paul Knaebel, Mechanical Maintenance Engineer, Washington State Department of Transportation (WSDOT)

Summary

During the visit additional details were obtained regarding the design, installation, maintenance and operating history of the anchor rods used in the Hood Canal Bridge. This type of information is being assembled, together other information obtained from review of project records, in a report prepared and periodically updated by BAMC [0]. That report should be consulted for details on the design, installation, maintenance and operating history of the anchor rods.

Long high strength 3 inch and 4 inch diameter A354BD anchor rods are used as part of structures that support guide rollers that position the movable draw spans of the floating bridge. The west section of the bridge has been in operation for about 32 years, while the east section has been in operation for about 4 years. Summary information for these two parts of the bridge is discussed below.

The anchor rods on the older west pontoons, which went into service about 32 years ago, were not zinc coated but rather are black and are protected with grease in the

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

duct embedded in the pontoon concrete, which is approximately the lower 15 feet of the 20 foot long rods. The upper portions of the rods, parts of which are inside box girders and parts of which extend above the box girders, were painted with the WSDOT three coat paint system, together with associated nuts and washers. The lower portion of the rods together with associated nuts and washers were also painted with the WSDOT three coat paint system. There have been no SCC failures of these rods. The 3 in. diameter rods are believed to have been pretensioned to 0.78 Fu, and in the 4 in. diameter rods were believed to have been pretensioned to 0.53 Fu. The satisfactory experience of the west side rods for 32 years with no SCC despite the relatively harsh marine environment indicates that greased and sheathed designs combined with blasted and painted exposed areas provide good long term protection against corrosion induced SCC.

Before the new east pontoons went into operation, at least three of the 3 inch rods failed in the shipyard in March 2009 shortly after being tensioned and at least six of the 3 inch rods were replaced. A review of information regarding those failures is contained in report of a previous visit, Reference [0].

The anchor rods on the newer east pontoons went into service about 4 years ago subsequent to replacement of some of the rods as noted above. These rods were hot dip zinc galvanized and are protected with grease in the duct embedded in the pontoon concrete, which is approximately the lower 15 feet of the 20 foot long rods. The upper portions of the rods, parts of which are inside box girders and parts of which extend above the box girders, were painted with the WSDOT three coat paint system on top of the zinc coating, together with associated nuts and washers. The lower portion of the rods together with associated nuts and washers were also painted on top of the zinc coating with the WSDOT three coat paint system. It appears that the top 7 inches of at least one of these rods was grit blasted to remove the zinc coating and then given the standard WSDOT three coat paint treatment. There have been no SCC failures of these rods. The 3 in. diameter rods are believed to have been pretensioned to 0.70 Fu, and the 4 in. diameter rods are believed to have been pretensioned to 0.53 Fu. The satisfactory experience of the east side rods for 4 years with no SCC despite the presence of galvanization and despite the relatively harsh marine environment indicates that galvanized rods that are protected using a combination of greased and sheathed methods and a three coat WSDOT paints system on top of galvanizing for non-sheathed areas provides protection against SCC for at least 4 years.

There are some uncertainties regarding the specific materials and hardness values of the anchor rods. Suggestions for resolving these uncertainties are discussed below.

Recommendations

It would be useful to know with greater certainty the alloy used and the hardness of the anchor rods used in the Hood Canal Bridge. It is suggested that efforts be made to

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

have the hardness determined at the top ends of each of the rods using portable hardness testers. It is further suggested that the alloy composition be determined using portable X-ray equipment. Both of these checks are relatively easy to perform, although they require the top of the rod to be polished to remove the coating that currently covers the ends and to provide a flat surface for hardness testing

It is understood that efforts are underway to try to obtain the material test reports for all of the A354BD rods used in both parts of the bridge. It is recommended that this effort be pursued and that the records be checked to determine if the steel used for the rods that failed in 2009 were vacuum degassed or not. The reason behind this suggestion is that lack of vacuum degassing is considered as being a possible factor in the hydrogen embrittlement failures of the 2008 anchor rods of the San Francisco Oakland Bay Bridge.

References

BAMC report "High Strength Anchor Bolts, Greased and Sheathed Double Corrosion Protection Systems, Hood Canal Bridge - WASHDOT," Draft Revision 10, July 11, 2013.

BAMC report, Report of June 28, 2013 Visit to Hood Canal Bridge and to Dwight Company, draft dated July 18, 2013.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

Appendix C

**COC's, CMO's, MTR's East Half Original Bolts,
Thompson Metal Fab/DYSON**

DRAFT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

KIEWIT - GENERAL, A JOINT VENTURE
HOOD CANAL BRIDGE #21150
 1202 Port of Tacoma Road
 Tacoma, WA 98421
 PH: (253) 439-6155
 FAX: (253) 439-6199

MOB
Project Team
 FEB 28 2008

**Hood Canal Bridge Retrofit
 And East Half Replacement**

TRANSMITTAL

TO: Jennifer Caldwell	DATE: 02/26/2008
WA. DEPARTMENT OF TRANSPORTATION 950 Broadway Suite 501 Tacoma, WA 98402	TRANSMITTAL NO. 2020
	SUBJECT Box Girder - Misc Hardware - COC, CMO
	REPLY TO: Alexis Marshall

WE ARE SENDING YOU: HEREWITH UNDER SEPARATE COVER OTHER

DATE	DESCRIPTION	QUANTITY
2/26/2008	COC - Stainless steel shims, galvanized embeds, anchor bars, and hex nuts	
2/26/2008	CMO - Stainless steel shims, galvanized embeds, anchor bars, and hex nuts	

THESE ITEMS ARE TRANSMITTED AS CHECKED BELOW:

- For Approval. Please return _____ copies with approval and any corrections and/or notations.
- Approved / Disapproved by: _____
- For you to submit a Proposal on work indicated as being revised. Please submit an "Add", "Deduct", or "No Change" proposed adjustment to your contract amount and indicate if the revision affects the schedule for your work.
- For pricing only. Do not proceed with construction until notified.
- For construction use, proceed immediately.
- For your general information. For your review and comments For your signature.
- Permanent Material? RAM#: QPL #Q512

Please respond by _____

REMARKS:	

Please contact us promptly if there is a problem or question.

Very Truly Yours,

By Alexis Marshall

Kiewit - General, A Joint Venture

Copy To: 1. File-Marilyn 2. _____ 3. _____ 4. _____

CERT. OF COMPLIANCE FOR ORIGINAL 3" x 4" ROSS. (NO MILL CERTS INCLUDED)

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



THOMPSON METAL FAB, INC.

3000 SE HIDDEN WAY • P.O. BOX 5276 (98668) • VANCOUVER • WA 98661
PH 360.696.0811 PORTLAND 503.283.4494 • FX 360.693.1017

Page 1 of 3

CERTIFICATE OF COMPLIANCE

DATE: 26 February 2008
TMF JOB NO.: 18010
CUSTOMER: Kiewit-General
CONTRACT / P.O. NO.: (TMF) 100010 (WSDOT) 6525
PART DESCRIPTION: See page 2 and 3

QTY

Bid Item: 162

In conformance with Section 1-06.3, 6-03.2 and 9-07 of the Washington State Department of Transportation Standard Specifications for Road, Bridge and Municipal Construction, we certify that the steel used in the fabrication of the items listed on this Certificate of Compliance has been manufactured, tested, and found to be in compliance with the above specifications. All materials used are of 100% domestic content and, throughout fabrication; the identification of steel has been maintained according to the above specification.

Brian J. Brace

Brian J. Brace
Quality Assurance Manager

26 February 2008

Date

Form Q-035 R/2



HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



THOMPSON METAL FAB, INC.

3000 SE HIDDEN WAY • P.O. BOX 5276 (98668) • VANCOUVER • WA 98651
 PH 360.696.0811 PORTLAND 503.283.4494 • FX 360.693.1017

CERTIFICATE OF CONFORMANCE

Page 2 of 3

DATE:

26 February 2008

QTY	Description
28	MK 05A, 20 GA. S.S. SHIM 20" X 42"
14	MK 05A, 16 GA. S.S. SHIM 20" X 42"
14	MK 05A, 11 GA. S.S. SHIM 20" X 42"
14	MK 05A, 1/4" S.S. SHIM 20" X 42"
12	MK 05B/C, 20 GA. S.S. SHIM 14-1/2" X 43" W 4" HOLES
16	MK 05B/C, 20 GA. S.S. SHIM 14-1/2" X 43" WITH 4-1/2" HOLES
6	MK 05B/C, 16 GA. S.S. SHIM 14-1/2" X 43" WITH 4" HOLES
8	MK 05B/C, 16 GA. S.S. SHIM 14-1/2" X 43" WITH 4-1/2" HOLES
6	MK 05B/C, 11 GA. S.S. SHIM 14-1/2" X 43" WITH 4" HOLES
8	MK 05B/C, 11 GA. S.S. SHIM 14-1/2" X 43" WITH 4-1/2" HOLES
6	MK 05B/C, 1/4" S.S. SHIM 14-1/2" X 43" WITH 4" HOLES
8	MK 05B/C, 1/4" S.S. SHIM 14-1/2" X 43" WITH 4-1/2" HOLES
28	MK 05B/C, 20 GA. S.S. SHIM 14-1/2" X 43" NO HOLES
14	MK 05B/C, 16 GA. S.S. SHIM 14-1/2" X 43" NO HOLES
14	MK 05B/C, 11 GA. S.S. SHIM 14-1/2" X 43" NO HOLES
14	MK 05B/C, 1/4" S.S. SHIM 14-1/2" X 43" NO HOLES
4	MK 05B, MODIFIED EMBED
2	MK 05A, MODIFIED EMBED
16	MK 05F, 4" DIAMETER ANCHOR BARS, 20'-2" LONG WITH 2 HEX NUTS

Brian J Brace

Brian J Brace

Quality Assurance Manager

Form Q 035 R/2



HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



THOMPSON METAL FAB, INC.

3000 SE HIDDEN WAY • P.O. BOX 5276 (98668) • VANCOUVER • WA 98661
 PH 360 . 696 . 0811 PORTLAND 503 . 283 . 4494 • FX 360 . 693 . 1017

CERTIFICATE OF CONFORMANCE

Page 3 of 3

DATE:

26 February 2008

QTY	Description
18	MK 05G, 3" DIAMETER ANCHOR BARS, 20'-2" LONG WITH 2 HEX NUTS
9	MK 05D, 1-1/2" DIAMETER ANCHOR BAR, 5'-11" LONG WITH 2 HEX NUTS
7 B/O	
12 B/O	MK 05E, 1-1/2" DIAMETER ANCHOR BAR, 5'-4" LONG WITH 2 HEX NUTS
14	DWG. 03-18010-05, ITEM 05A, GALVANIZED EMBED WITH BONDED TEFLON
10	DWG. 03-18010-05, ITEM 05B, GALVANIZED EMBED WITH BONDED TEFLON
4	DWG. 03-18010-05 ITEM 05C, GALVANIZED EMBED WITH SHEAR STUDS
2	DWG. 03-18010-05 05G, 3" DIAMETER GALVANIZED THREADED ROD WITH 2 HEX NUTS (20'-2" LONG)
1	4" HEX NUT
8	MK 05D, 1-1/2" NC GALVANIZED ANCHOR ROD 5'-11" LONG
12	MK 05E, 1-1/2" NC GALVANIZED ANCHOR ROD 5'-4" LONG
40	1-1/2" NC GALVANIZED HEX NUT FOR ANCHOR RODS LISTED ABOVE

Brian J Brace
 Brian J Brace
 Quality Assurance Manager

Form Q-405 R/20 080



HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

 Washington State Department of Transportation		Certification of Materials Origin (Required for Acceptance of Steel Materials)	
Contract 100010		SR	
Section HOOD CANAL BRIDGE			
Contractor KIEWIT / GENERAL			
Subcontractor / Supplier THOMPSON METAL FAB, INC. 3000 SE HIDDEN WAY VANCOUVER, WA 98661			
Materials - Bid Item 162		Quantity	
Description STAINLESS STEEL SKIMS MODIFIED EMBEDS GALVANIZED EMBEDS		ANCHOR BARS HEX NUTS	

The following Certification of Materials Origin is made for the purposes of establishing materials acceptance under Contract Provisions entitled "Foreign-Made Materials." Materials as described above are furnished for use in compliance with the certification as noted in 1 or 2 below. Manufacturing processes for the materials are defined on the back of this form.

- 1. The materials covered by this certification are American-Made with all manufacturing processes entirely within the United States of America.
- 2. The materials furnished for this project under this certification contain steel or iron manufactured, all or in part, outside the United States of America.

The Description and Country of Origin of these materials is as follows:

The Invoice Cost for the above described foreign-made materials is:

I declare under penalty of perjury under the laws of the State of Washington that the foregoing is true and correct.

BRIAN BRACE
 Contractor / Subcontractor / Supplier Name
Brian J. Brace 26 FEBRUARY 2008 THOMPSON METAL FAB, INC.
 Authorized Corporate Official Signature Date Place

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



THOMPSON METAL FAB, INC.
 P.O. BOX 5276 (98668), VANCOUVER, WA 98661
 Tel: (503) 283-4494, (360) 896-0811 Fax: (360) 693-1017
 www.thompsonmetalfab.com

PURCHASE ORDER: 18010-10636		This number must appear on all invoices and shipping papers	
Issued to: DYSON CORPORATION, THE 53 FREEDOM ROAD PAINSVILLE, OH 44077 Tel: 800-680-3600-202 Fax: 440-352-2700 Attn: PETER		Ship to: THOMPSON METAL FAB, INC. 3000 SE HIDDEN WAY, BLDG. 40 VANCOUVER, WA 98661	
Ship via: DELIVER FOB Point: TMF Shop Order: TAYLOR [x] Domestic steel only		Issued: 09-15-04 Deliver by: 11-24-04 A.M. Terms: NET 30 Resale #: - C600-094-986 [x] Material Test Reports Required	
Please provide prices and delivery schedule before shipping. Notify us immediately if shipping schedule cannot be met.			

No.	Quan	Type	Size	Grade	Length	Weight	Unit Price	Price
1	8			A354 GR BD	249"			
4" ANCHOR ROD - PER DRAWING 03-18010-05 - MK 05F (ITEM 13) INCLUDES (16) M291 GR DH 4" NUT								
2	20			A354 GR BD	242"			
3" ANCHOR ROD - PER DRAWING 03-18010-05 - MK 05G (ITEM 14) INCLUDES (40) M291 GR DH 3" NUT								
ALL WITH ROLLED THREADS AND GALVANIZED								
3	1		FREIGHT					
Notes: CLASS II - 100% DOMESTIC								



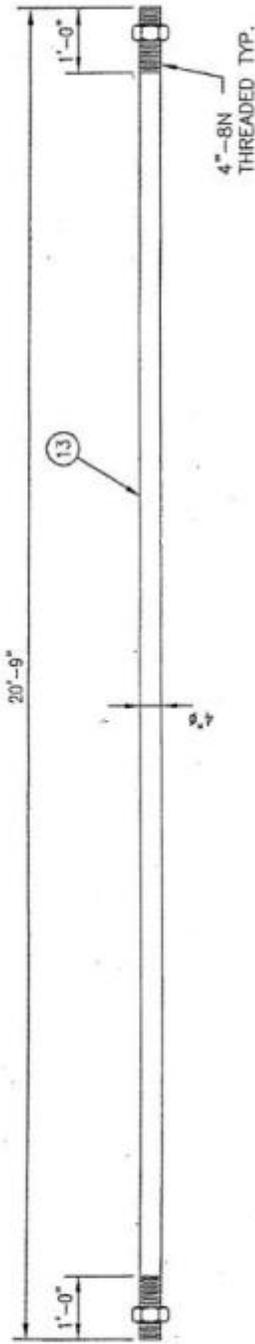
PLEASE ACKNOWLEDGE!

Item #1.
 A043600-05-2631-6/9/05
 38642-05-2632-6/9/05

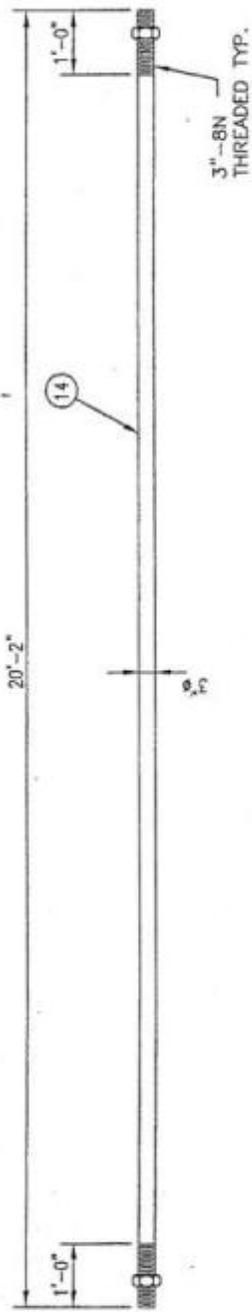
Item #2.
 56588-05-2633-6/9/05
 557326-05-2634-6/9/05

Signature: _____

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



MK 05F - ANCHOR ROD - (8) REQ'D
SCALE: 1/2" = 1'-0"



MK 05G - ANCHOR ROD - (20) REQ'D
SCALE: 1/2" = 1'-0"

03-18010-05
REV 7/11/77

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED TEST REPORT

DYSON CORP.

DYN DOMESTIC NUT

53 Freedom Road
Painesville, OH 44077

440-946-3500
440-352-2700 fax

1

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 71099	18010-10636	1 of 5	8 pcs	5/31/05

CUSTOMER
Thompson Metal Fab, Inc.
PO Box 5276
Vancouver, WA 98668

USA

DRAWING

PRODUCT DESCRIPTION
4.00"-8UN-2A x 249.00" OAL double end stud with rolled threads & 12.00" thread length each end.
HDGper ASTM-A153. Dwg.# 03-18010-05-MK 05F

SPECIFICATIONS
ASTM-A354 Grade BD

STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	4.563	BD	8	KAS	A043600	Steel Dynamic

05-7631

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.
1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.

PO.	18010-10636
MTN	05-7631
QC	MAB
DATE	6/9/05

Attachments:
Mill Test Report
Mechanical Test Report

Deborah A. Smith
Deborah A. Smith
Q.A. Admin. Assistant
5/31/05

LARGE DIAMETER FASTENERS & FORGINGS / STANDARDS & SPECIALS / COMMERCIAL, MILITARY & NUCLEAR SPECIFICATION

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



8000 N. County Road 225 East
 Pittsboro, IN 46187
 Telephone: (317) 892-7188
 Fax: (317) 892-7288

Page 1 of 1
 Date: 12/30/2004
 Time: 08:22:48
 Report No: 900

CODE KAS

Certified Material Test Report

Certificate: 5755 Sales Order: 3079 Heat: AD43E00 Size: 4-9/16"
 Revision: 1 Customer: Jade Sterling Mill Order: CAC0648 Shape: ROUND
 Issued: 12/21/2004 PO: 83357 Work Order: 10450 Length: 24' 05"
 Grain Practice: Fine Part No: Grade: 4140/42 Reduction Ratio: 8.34 : 1

Chemistry														
C	Mn	P	S	Si	Al	Cu	Ni	Cr	Mo	Sn	N	V	Nb	W
0.42	0.87	0.022	0.025	0.28	0.029	0.27	0.08	0.95	0.16	0.011	0.0059	0.003	0.005	0.010
Ti	B	Ca	Pb	Co	Oi									
0.002	0.0003	0.0014	0.001	0.007	5.23									

Jominy														
J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J12	J14	J16	J18	J20
57	57	57	57	57	57	56	55	54	52	50	48	46	45	45
J24	J28	J32												
42	40	39												

Magna		
S	R	C
1	2	2

05-2631

Comments
 ASTM A322 (latest rev.)

PO
 18010-10634
 MTM
 05-2631
 QC
 M+B.
 DATE
 6/9/05

DESIGNED
 2/1/05
 BY SUN

Insured to 4' 0"
 by Best Steel

I hereby certify that the contents of this report are accurate and correct.
 All tests and operations performed by the material manufacturer are in compliance with the requirements of the material specifications and applicable purchaser designated requirements.
 Any alterations to this report voids Steel Dynamics' warranting of results. No weld repair has been performed on this material. Steel with a reharder Al content of 0.020% or greater is considered fine grained (3-4) per ASTM A322.
 This material is not radioactive and has not been exposed to radioactivity while under the control of Steel Dynamics. Unless otherwise noted, this material was melted, continuously cast and rolled in the USA. This material has not been exposed to mercury while under the control of Steel Dynamics.

Signed: *L. K.*

FEB-04-2005 16:07 JADE STERLING STEEL 317-892-7248 P. 01/01

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



TC INDUSTRIES TEST CENTER
 3703 South Route 31
 Crystal Lake, IL 60012-1412
 Telephone 815/459/2400 Fax 815/459/3419



Certificate No. 1281-01

REPORT NO: 121163
 DATE: FEBRUARY 24, 2005
 PAGE 1 OF 1

TO: THE DYSON CORP.
 53 FREEDOM ROAD
 PAINESVILLE, OH 44077

SHIP TO: THE DYSON CORP.
 53 FREEDOM ROAD
 PAINESVILLE, OH 44077

CODE KAS

Slo C71099

DESC:	9 PCS	4.563"RD X 24"9"	HEAT#: A043600	GRADE: 4140	WT: 12560
		PO: 39768	MO: 104472	CO: 39677	LOT: 40536
SPEC:	QUENCH, TEMPER ONLY		ASTM A354-BD-04		
PROCESS:	FURN TEMP :	1600	FURN TIME hh:mm:	3.55	QUENCH: WATER
	TEMPER TEMP:	1050	TEMPER TIME hh:mm:	4.55	
	STRESS TEMP:		STRESS TIME hh:mm:		
PARAMETER	UNITS	LIMITS	TEST RESULTS (See sampling plan on back)		
TENSILE	KSI	140 N/A	146.000		
YIELD .2%	KSI	115 N/A	124.000		
ELONG 2"	%	14 N/A	14.0		
RED AREA	%	40 N/A	42.0		
SURF HB	HBW	293 363	321	321	321

TC INDUSTRIES AND SUBCONTRACTED LABS (A2LA ACCREDITED)

Tensile, Standard	TC	Rockwell		Micro Analysis
Tensile, Full Secn		Brinell	TC	Decarb Measure
Charpy V 10mmx10mm		Spectro*		
Microhardness, Knoop*		Macroetch		
TC: TC Ind Test Center	SS: Staveley Services	MSI: Metallurgical Services		
Cert #1281-01	Cert #0286-01	Cert #0510-01		
Expires 02/28/05	Expires 08/30/06	Expires 02/28/05		

*Not included in our scope of accreditation

TIME .08:16
 DATE IN: 2/02/05
 FC 4.12.16 E 05/08/03

Ken Rueff
 Ken Rueff
 Test Center Supervisor

05-2631

18010-10636
 05-2631
 TC DATE
 MAR. 6/7/05

There are no deviations from test methods unless noted. It should not be assumed that mechanical properties of raw material heat treated to a fastener standard will have the same properties of a finished fastener whose original material characteristics may have been significantly altered.

No mercury was used/added and no weld/re-weld repair was performed on this material while in the possession of TC Industries, Inc.

This original test report displays a raised "TC Industries Test Center" seal. This test report relates only to the items tested and shall not be reproduced, except in full, without the written permission of TC Industries Test Center

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

DRAFT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED TEST REPORT				
 DYSON CORP.  DOMESTIC NUT	53 Freedom Road Painesville, OH 44077	440-946-3500 440-352-2700 fax	<i>4" nuts #1</i>	

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 71100	18010-10636	2 of 5	16 pcs	5/31/05

CUSTOMER Thompson Metal Fab, Inc. PO Box 5276 Vancouver, WA 98668 USA	PRODUCT DESCRIPTION 4.00"-8UN-2B (.031" oversize) heavy hex nut, HDG per ASTM-A153 SPECIFICATIONS AASHTO M 291 Grade DH (ASTM-A563 Gr. DH)
DRAWING Dyson Std	

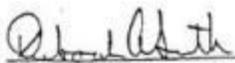
STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	4.000	1045	16	GXM	38642	GST Steel

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.

1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.
2. Hardness Results: 269 HBW

P.C.
18010-10636
MTN
05-2632
CC *DATE*
MAB 6/9/05

Attachments:
 Mill Test Report


 Deborah A. Smith
 Q.A. Admin. Assistant
 5/31/05

LARGE DIAMETER FASTENERS & FORGINGS / STANDARDS & SPECIALS / COMMERCIAL, MILITARY & NUCLEAR SPECIFICATION

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

FAX 202 10:11

JADE STERLING STEEL

330 425 3056 P. 02/04

JUL 25, 1999 8:54AM
TO: JADE STERLING STEEL

GST KCMO SALES

NO. 623 P. 1/1

MILL TEST REPORT

GST Steel Company
7000 Roberts
Kansas City, MO 64125

MTR-040

12-9-98
Page 1 of 1

CODE GXM

FAX TO
Jade Sterling
Mike Manfield
330 425-3056
Po # 26161

3.75" HR RD A105		MPa	P	S	SI	MPa	SI	MPa	SI	V	SI	SI
LOT	C	MPa										
38268	21	.97	.007	.005	25	.8	10	.019	.19	.004	.000	.010
38630	19	.91	.011	.022	11	.8		.019	.19	.004	.000	.012

3.75" HR RD 1045		MPa	P	S	SI	MPa	SI	MPa	SI	V	SI	SI
LOT	C	MPa										
38639	48	.67	.009	.009	11	.8	8.0	.014	.19	.004	.000	.010

4" HR RD 1045		MPa	P	S	SI	MPa	SI	MPa	SI	V	SI	SI
LOT	C	MPa										
38430	48	.64	.009	.007	24	.8	11.0	.015	.17	.003	.000	.008
38641	45	.83	.022	.011	24	.8	11.0	.021	.18	.004	.000	.010
38642	46	.70	.010	.014	11	.8	11.0	.021	.19	.004	.000	.010

05-2632

THE ABOVE TEST DATA IS TO CERTIFY THAT THE MATERIAL IS IN CONFORMANCE WITH THE ORDER'S SPECIFICATION.

ISSUED BY QUALITY ASSURANCE - V. C. Van Slyke

Craig Van Slyke

Melted and Manufactured in U.S.A.
Melted by GS Industries

2/22/02
Next 38642

18010-10636
05-2632
DATE 6/9/02
GXM

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED TEST REPORT

 DYSON CORP.

 DOMESTIC NUT

53 Freedom Road
Painesville, OH 44077

440-946-3500
440-352-2700 fax

#2

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 71103	18010-10636	3 of 5	20 pcs	5/31/05

CUSTOMER
Thompson Metal Fab, Inc.
PO Box 5276
Vancouver, WA 98668

USA

DRAWING

PRODUCT DESCRIPTION
3.00"-8UN-2A x 242.00" OAL double end stud with 12.00" thread length each end (rolled threads) per Dwg. # 03-18010-05-MK 05G. HDG per ASTM-A153

SPECIFICATIONS
ASTM-A354 Grade BD

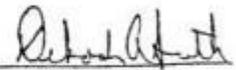
STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	3.250	4140	20	JWF3	S67588	North Star

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.
1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.

05-2633

18010-10636
05-2633
DATE 6/9/05
MWB

Attachments:
Mill Test Report
Mechanical Test Report


Deborah A. Smith
Q.A. Admin. Assistant
5/31/05

LARGE DIAMETER FASTENERS & FORGINGS / STANDARDS & SPECIALS / COMMERCIAL, MILITARY & NUCLEAR SPECIFICATION

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



TC Industries Test Center
 3703 South Route 31
 Crystal Lake, IL 60012-1412
 Telephone 815/459/2400 Fax 815/459/3419



Certificate No. 1281-01

TEST REPORT
REPORT NO: 121156
 DATE: MARCH 15, 2005
 PAGE 1 OF 1

TO: THE DYSON CORP.
 53 FREEDOM ROAD
 PAINESVILLE, OH 44077

SHIP TO: THE DYSON CORP.
 53 FREEDOM ROAD
 PAINESVILLE, OH 44077

DESC: 24 PCS	3 1/4"RD X 24"	HEAT#: S67588	GRADE: 4140	WT: 16250		
	PO: 39768	MO: C71103	CO: 39768	LOT: 40587		
SPEC: QUENCH, TEMPER, STRAIGHTEN	STRESS RELIEVE					
ASTM A354-BC-04						
PROCESS:	FURN TEMP : 1600	FURN TIME hh:mm: 2.25	QUENCH: OIL			
	TEMPER TEMP: 1100	TEMPER TIME hh:mm: 3.25				
	STRESS TEMP: 1000	STRESS TIME hh:mm: 3.25				
PARAMETER	UNITS	LIMITS	TEST RESULTS (See sampling plan on back)			
TENSILE	KSI	140 N/A	149.508			
YIELD .2%	KSI	115 N/A	126.902			
ELONG 2"	%	14 N/A	16.5			
RED AREA	%	40 N/A	51.7			
SURF HB	HBW	293 363	311	311	311	331

TC INDUSTRIES AND SUBCONTRACTED LABS (A2LA ACCREDITED)

Tensile, Standard	SS	Rockwell		Micro Analysis
Tensile, Full Secn		Brinell	TC	Decarb Measure
Charpy V 10mmx10mm		Spectro*		
Microhardness, Knoop*		Macroetch		
TC: TC Ind Test Center	SS: Staveley Services	MSI: Metallurgical Services		
Cert #1281-01	Cert #0286-01	Cert #0510-01		
Expires 02/25/07	Expires 06/30/06	Expires 12/31/06		

*Not included in our scope of accreditation

TIME 08:12
 DATE IN: 2/03/05

Kan Ruelf
 Kan Ruelf
 Test Center Supervisor

FC 4.12.16 F 02/25/05

05-2633

S/O C71103

18010-10636
 05-2633
 MAB DATE 3/9/05

There are no deviations from test methods unless noted. It should not be assumed that mechanical properties of raw material heat treated to a fastener standard will have the same properties of a finished fastener whose original material characteristics may have been significantly altered.

No mercury was used/added and no welding/weld repair was performed on this material while in the possession of TC Industries, Inc.

This original test report displays a raised "TC Industries Test Center" seal. This test report relates only to the items tested and shall not be reproduced, except in full, without the written permission of TC Industries Test Center.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



P.O. Box 64189
1678 Red Rock Road
Saint Paul, Minnesota 55164

Product: Round Bar
Grade: A4140FA
Date Rolled: 10/26/2004
P.O: 366-7
M.O #: 242823

CERTIFIED TEST REPORT

CODE JWF3

CHEMICAL ANALYSIS (WT %)

C	Mn	P	S	Si	Sn	Cu	Ni	Cr	Mo	Cb	V	Co	Al	Ti	Ca _{ppm}	N _{ppm}
0.40	0.87	0.012	0.020	0.21	0.005	0.24	0.11	0.92	0.17	0.003	0.027	0.009	0.002	0.003	7	89

MATERIAL 100% MELTED AND ROLLED IN THE USA. MANUFACTURING PROCESSES FOR THIS STEEL, WHICH MAY INCLUDE SCRAP MELTED IN AN ELECTRIC ARC FURNACE AND HOT ROLLING, HAVE BEEN PERFORMED AT NORTH STAR STEEL MINNESOTA, 1678 RED ROCK ROAD, SAINT PAUL, MINNESOTA, USA. ALL PRODUCT PRODUCED FROM STRAND CAST BILLETS. NO WELD REPAIRMENT PERFORMED. STEEL NOT EXPOSED TO MERCURY OR ANY LIQUID ALLOY WHICH IS LIQUID AT AMBIENT TEMPERATURES DURING PROCESSING OR WHILE IN NORTH STAR STEEL MINNESOTA POSSESSION.

JOMINY END QUENCH HARDENABILITY RESULTS (HRc)

J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12
56	56	56	56	56	56	55	53	52	50		47
J13	J14	J15	J16	J18	J20	J22	J24	J26	J28	J30	J32
	46		43	43	42		41		38		36

Jominy Calculated Per ASTM A255-99

MECHANICAL TEST REPORT

SPECIMEN AREA (in ²)	YIELD (Kip)	YIELD (Ksi)	TENSILE (Kips)	TENSILE (Ksi)	GAUGE LENGTH (in)	% ELONG	BEND	% R.A.

Additional Specifications/Comments:
A354-03a (Chemistry Only)

Q.A. REVIEWED
DATE 11/3/04
DYSON

Revised to 3/2
by Peter Shaver

Grain Size: 7-5 Reduction Ratio: 08.2:1 C.E. Part: _____ As Rolled surface Hardness: _____
 Coding: _____ D.I.: 5.11 in. Ms: 610.9 Deg F. C.E.: _____ HBW: 277 HRc: _____
 Test 1: _____ Test 2: _____

CHARPY IMPACT TEST

* : Test 1 Test 2
Temp (F) :
ft-lb 1
ft-lb 2
ft-lb 3

ASTM E45 is not a laboratory accredited test.

Micro Clean Average
 At: Ah: Bt: Bh: Ct: Ch: Dt: Ds: S-Rating O-Rating:

Macro Etch: S2-R2-C1

The above results relate only to the items tested.

Chemical tests performed in accordance with ASTM E415 and E1019. Mechanical tests performed in accordance to ASTM E8, E10, E16, E290 and A370. All other tests performed in accordance with the requirements of applicable specifications unless otherwise noted above. We hereby certify that the above test results are representative of those contained in the records of the company.

Any modification to this certificate as provided by North Star Steel Minnesota without the expressed written consent of North Star Steel Minnesota negates the validity of this test report. This report shall not be reproduced except in full, without the expressed written consent of North Star Steel Minnesota. North Star Steel Minnesota is not responsible for the inability of this material to meet specific applications.

ASTM Test Method

Accredited to:	ASTM A370	ASTM E8	ASTM E10	ASTM E16	ASTM E23	ASTM E112	ASTM E288	ASTM E290	ASTM E415	ASTM E1019
ISO 17023	X	X	X	X				X	X	X
subcontractor (ISO 17025)		*			*	*	*			

X North Star Steel Minnesota, A2LA Certification #1055-01 Exp. 6/30/06
 * Denotes Testing By Sub-Contractor:
 Metallurgical Services Inc., A2LA Certification #510-01 Exp. 12/31/04
 Stork Twin City Testing, A2LA Certification #1479-01 Exp 12/31/04
 Measurement of uncertainty information is available upon request.

SIGNED: _____
 DATE: 10/29/2004
 APPROVAL: _____
QA Approval
Peter L. Shaver
 Peter Shaver

SWORN AND SUBSCRIBED TO BEFORE ME
 THIS _____ DAY _____

 (NOTARY PUBLIC)
 THIS CERTIFICATE IS NOTARIZED ONLY WHEN REQUESTED

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED TEST REPORT

 DYSON CORP.
 DOMESTIC NUT

53 Freedom Road
 Painesville, OH 44077

3" NUTS.
 #2

440-946-3500
 440-352-2700 fax

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 71104	18010-10636	4 of 5	40 pcs	5/31/05

CUSTOMER
 Thompson Metal Fab, Inc.
 PO Box 5276
 Vancouver, W.A. 98668
 USA

PRODUCT DESCRIPTION
 3.00"-8UN-2B (.031" oversize) heavy hex nut, HDG per ASTM-A153

SPECIFICATIONS
 AASHTO M 291 Grade DH (ASTM-A563 Gr. DH)

DRAWING
 Dyson Std

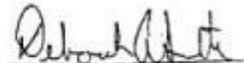
STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	3.500	1045	40	JHU2	S57326	North Star

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.
 1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.
 2. Hardness Results: 255/269 HBW

OS-2635

18010-10636
 OS-2635⁰⁵
 DC DATE
 MAR 6/9/05

Attachments:
 Mill Test Report


 Deborah A. Smith
 Q.A. Admin. Assistant
 5/31/05

LARGE DIAMETER FASTENERS & FORGINGS / STANDARDS & SPECIALS / COMMERCIAL, MILITARY & NUCLEAR SPECIFICATION

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

THE DYSON CORPORATION
HOT ROLLED ROLDS 1045
3.5000 X 20"
PART NO.

PO/Rel J-238
I hereby certify that the data is correct as
contained in the records of this company.

Att: _____

8-27-03: 7:57AM: NISS SHIPPING

1551735+695



NORTH STAR STEEL MINNESOTA

P.O. Box 54188
1678 Red Rock Road
Saint Paul, Minnesota 55184

Heat #:	SS7325
Size:	3 1/2"
Product:	Round Bar
Grade:	MS-1045CF
Date Rolled:	8/7/2003
P.O.	87164
M.O #:	230789
	AS76-90B

CERTIFIED TEST REPORT

CODE JHWZ

CHEMICAL ANALYSIS (WT %)

C	Mn	P	S	Si	Sn	Cu	Ni	Cr	Mo	Cb	V	Co	Al	Ti	Ca	N
0.44	0.69	0.009	0.024	0.21	0.005	0.23	0.08	0.14	0.01	0.018	0.002	0.0080	0.003	0.0030	20	79

MATERIAL 100% MELTED AND ROLLED IN THE USA. MANUFACTURING PROCESSES FOR THIS STEEL, WHICH MAY INCLUDE SCRAP MELTED IN AN ELECTRIC ARC FURNACE AND HOT ROLLING, HAVE BEEN PERFORMED AT NORTH STAR STEEL MINNESOTA, 1678 RED ROCK ROAD, SAINT PAUL, MINNESOTA, USA. ALL PRODUCT PRODUCED FROM STRAND CAST BILLETS. NO WELD REPAIRMENT PERFORMED. STEEL NOT EXPOSED TO MERCURY OR ANY LIQUID ALLOY WHICH IS LIQUID AT AMBIENT TEMPERATURES DURING PROCESSING OR WHILE IN NORTH STAR STEEL, MINNESOTA POSSESSION.

JOMINY END QUENCH HARDENABILITY RESULTS (HRc)

J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12
J13	J14	J15	J16	J18	J20	J22	J24	J26	J28	J30	J32

MECHANICAL TEST REPORT

SPECIMEN AREA (in ²)	YIELD (Kpsi)	YIELD (ksi)	TENSILE (Kpsi)	TENSILE (ksi)	GUAGE LENGTH (in)	% ELONG	BEND	% R.A.	SPECIFICATION / GRADE
C202	11.0	54.4	20.2	100.1	2.00	17.00		22	MS-1045CF

05-2634

15010-10636
05-2634
MMP DATE 6/9/05

Additional Specifications/Comments:
A29/A29M-99#1
ASTM-90b (2000)

Grain Size: Reduction Ratio: C.E. Per:
Coiling: D.I: in. M.S: Deg F. C.E.:
As Rolled surface Hardness
Bhn: HRc:
Test 1:
Test 2:

CHARPY IMPACT TEST

Temp (F)	Test 1	Test 2
T-b 1		
T-b 2		
T-b 3		

Micro Clean Average
Al: Al2: Si: S: C: Cr: D: D1: S-Rating: O-Rating:
Macro Etch:

ASTM Test Method

ASTM	ASTM	ASTM	ASTM	ASTM	ASTM	ASTM	ASTM	ASTM	ASTM
A370	E8	E18	E18	E22	E112	E225	G99	B415	E1019
MS-1045CF	X	X	X	X			X	X	X
ISO Grade 28 AND 34								X	X
ISO Grade 28									

The above results relate only to the items tested.
* Denotes tests performed by subcontractors in accordance with ASTM standards.
Chemical tests performed in accordance with ASTM E415 and E1019.
Mechanical tests performed in accordance to ASTM E8, E10 and A370. All other tests performed in accordance with the requirements of applicable specifications unless otherwise noted above. We hereby certify that the above test results are representative of those contained in the records of the company.

X North Star Steel Minnesota, AZLA Certificate #1065-01, Exp. 5/30/04
* Denotes Testing By Sub-Contractor:
Metallurgical Services Inc., AZLA Cert # 510-01, Exp. 12/31/04
Stork Twin City Testing, AZLA Cert # 1479-01, Exp. 12/31/04

Any modification to this certificate as provided by North Star Steel Minnesota without the expressed written consent of North Star Steel Minnesota negates the validity of this test report. This report shall not be reproduced except in full, without the expressed written consent of North Star Steel Minnesota. North Star Steel Minnesota is not responsible for the inability of this material to meet specific applications.

SIGNED: _____
DATE: 08/27/2003
QA Approval
Pete L. Pham

SWORN AND SUBSCRIBED TO BEFORE ME
THIS _____ DAY _____

Q.A. REVIEWED
DATE 1/15/04
DYSON

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

Appendix D

MTR's, Replacement Bolts, East Half

Portland Bolt/Galvanizers CO

DRAFT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

KIEWIT - GENERAL, A JOINT VENTURE
 HOOD CANAL BRIDGE #21150
 1202 Port of Tacoma Road
 Tacoma, WA 98421
 PH: (253) 439-6155
 FAX: (253) 439-6199

HCB
 Project Team
 2003

Hood Canal Bridge Retrofit
 And East Half Replacement

K-6
 WSDOT
 INSPER

TRANSMITTAL

TO: <u>J. Caldwell</u>	DATE: <u>6/26/2003</u>
WA. DEPARTMENT OF TRANSPORTATION 950 Broadway Suite 501 Tacoma, WA 98402	TRANSMITTAL NO. <u>2424</u>
	SUBJECT <u>Portland Bolt Replacement Box Girder Bolt</u>
	REPLY TO: <u>Fred Fleming</u>

WE ARE SENDING YOU: HEREWITH UNDER SEPARATE COVER OTHER

DATE	DESCRIPTION	QUANTITY
<u>6/26/2003</u>	<u>Packing list, CMO and COC 6ea - 3" x 20'-6" A354 BD Rods RFT 1314</u>	<u>1</u>

THESE ITEMS ARE TRANSMITTED AS CHECKED BELOW:

- For Approval. Please return _____ copies with approval and any corrections and/or notations.
- Approved / Disapproved by: _____
- For you to submit a Proposal on work indicated as being revised. Please submit an "Add", "Deduct", or "No Change" proposed adjustment to your contract amount and indicate if the revision affects the schedule for your work.
- For pricing only. Do not proceed with construction until notified.
- For construction use, proceed immediately.
- For your general information. For your review and comments For your signature.
- Permanent Material? RAM#: 13324

Please respond by ASAP

REMARKS:	

*LETS FOR
 REPLACEMENT 3" Ø RODS
 FROM PORTLAND BOLT.*

Please contact us promptly if there is a problem or question.

Very Truly Yours,

By Fred Fleming

Kiewit - General, A Joint Venture

Copy To: 1. File-Marilyn 2. _____

3. _____ 4. _____

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

1113 SHIPPING ORDER

Carrier's Name: **Jennings & Son**
 16848 Railway Rd S.E.
 Yelm, WA 98597

Shipper's No. 43785
 Carrier's No. 4760

RECEIVED subject to the classifications and tariffs in effect on the date of the issue of this order.

at Douglas (Date) 6-25-09 FROM Galumizis

Consigned TO Kiewit - General 40 Lafell Storage 1
On Certain Railway Equipment, the letters "C.O.D." appear below consignee's name or as otherwise provided on Item C-3, Sec. 1.

Destination Douglas Street 27080 State Hwy 3 City _____
 County _____ State WA Zip _____

Route _____ Delivery Address* _____
(*To be filled in only when shipper desires and governing tariffs provide for delivery direct.)

Delivering Carrier Daw J. Car or Vehicle Initials and No. 56-86

Collect on Delivery \$ _____ And Remit to _____

No. Packages	HTM	Kind of Package, Description of Articles, Special Marks, and Exceptions	Weight (Subject to Contract)	Class or Rate	Check Columns
<u>6</u>		<u>Threaded Rods with Nuts Attached 3" x 24"</u>			
		<u>Kiewit PO# 21150-KM1054</u>			

Signature of Consignor: _____

C. O. D. Charges to be Paid by:
 Shipper Consignee

Survived _____ in progress of the charge on the property described herein.

Agent or Clerk: _____

For (The signatory here acknowledges only the amount prepaid.)
 Charge Address: _____

1. The blue containers used for this shipment conform to the specifications set forth in the last edition's certificate of approval and all other requirements of Rule 41 of the Uniform Freight Classification and Rule 2 of the National Motor Freight Classification.

2. Shipper's liability in loss of cargo, not a part of bill of lading approved by the Interstate Commerce Commission.

Shipper, Per _____

Permanent post-office address of shipper: _____

Agent must detach and retain this Shipping Order and must sign the Original Bill of Lading - 24-09

2

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

GALVANIZERS COMPANY

**2406 N. W. 30TH AVENUE
PORTLAND, OREGON 97210**

TELEPHONE 503-227-5611

FAX 503-227-2558

June 29, 2009

Kiewitt-General
PO Box 232
Port Gamble, WA 98264-0232

To Whom It May Concern:

We hereby certify that the following material has been galvanized in accordance with specifications as set forth by ASTM-A-123/A-153. Final inspection has been made and the material meets all requirements.

Reference Date: 6/16/09

Reference No. 21150-KM1054

Material: 6pcs- 3" x 246" Anchor Rod

Sincerely,



Craig Hamilton
Operations Manager

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



PRODUCT CERTIFICATION

Mailing Address: PO Box 2866 • Portland, OR 97208
Physical Address: 3441 NW Guam St. • Portland, OR 97210
Phone: 503-227-5488 • Fax: 503-227-4834
Web: www.portlandbolt.com • E-Mail: sales@portlandbolt.com

For: KIEWIT-GENERAL/J.V.
PB Invoice#: 29578
Cust PO#: SEE COMMENTS
Date: 6/12/2009
Shipped: 6/15/2009

We certify the following material was supplied in accordance with your order.

Description: 3--8* X 246 BLK ASTM A354BD RODS

Heat#: 8091870	Base Steel: A354BD	Diam: 3
----------------	--------------------	---------

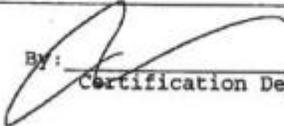
Source: KREHER STEEL CO LLC Proof Load: 0

C : .400	Mn: .740	P : .009	Hardness: 331 HBN
S : .005	Si: .240	Ni: 1.680	Tensile:161,000 PSI RA: 56.00%
Cr: .800	Mo: .210	Cu: .190	Yield: 144,000 PSI Elong: 18.00%
Pb: .000	V : .003	Cb: .001	Sample Length: 2 INCH
N : .000	CE: .6875	Charpy: 47 48 43	

CVN TEMP -20F

Nuts:
ASTM A563DH HVY HX

Coatings:
ASTM A153 CL.C AND F2329, HOT DIP GALV

By:  Certification Department Quality Assurance

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

KREHER STEEL COMPANY, LLC.
ANCHOR BOLT & MFG. CO. PO/Ref 96379
 11550 NORTH 28TH AVENUE Crystal Lake, IL 60012-1412 Telephone 815/468/2400 Fax 815/453/3419
 I hereby certify that this data is correct as contained in the records of this company. I hereby certify that no recovery came to contact.

Certificate of Mill Test Results
 SO 1 - 183796-001 8/Jan/09 Pg 1/1
 with or no weld repair was done to this product while in our possession. AISC

TC Industries Test Center
 3733 South Route 31
 Crystal Lake, IL 60012-1412
 Telephone 815/468/2400 Fax 815/453/3419



TEST REPORT
 REPORT NO: 144869
 DATE: MAY 29, 2009
 PAGE 1 OF 1

TO: KREHER STEEL CO. 1550 NORTH 28TH AVENUE MELROSE PARK, IL 60160
 SHIP TO: KREHER STEEL CO. 1550 NORTH 28TH AVENUE MELROSE PARK, IL 60160

DESC: 8 PCS	3"RD X 23 1/2"	HEAT#: 8091870	GRADE: 4340H	WT: 3480 #	
	PO: 1-116104	MO: 103428	CO: 110104	LOT: 64427	
SPEC: QUINCH, TEMPER, STRAIGHTEN	ASTM-A304 80-07A				
✓ CHARTY 18FT/LSB@-20F	✓				
PROCESS: FURN TEMP: 1800	FURN TIME MIN: 2.08	QUENCH: OIL			
TEMPER TEMP: 1078	TEMPER TIME MIN: 3.00				
STRESS TEMP:	STRESS TIME MIN:				
PARAMETER	UNITS	LIMITS	TEST RESULTS (See sampling plan on back)		
TENSILE	KSI	140 - N/A	161.0		
YIELD 2%	KSI	115 - N/A	144.0		
ELONG 2"	%	14 - N/A	18.5		
RED AREA	%	40 - N/A	55.0		
CHARPY	FT-LB	15 - N/A	47	48	43
CVN TEMP	F	-20 - -20			
SURF HB	HAW	293 363	331		

TO INDUSTRIES AND SUBCONTRACTED LABS (ASLA ACCREDITED)

Tensile, Standard	TC	Rockwell	TC	Micro Analytik
Tensile, Full Section		Brinell		Docub Measure
Charpy V 10ft/10cm	MBI	Spectro		Chemistry
Microhardness, Knoop		Macrostat		
TC: TC Ind Test Center Cert #1291-01 2/28/11	BC: Bodycote Services Cert #0286 8/30/10	MST: Metallurgical Services Cert #0510 12/21/10		

TIME 09:00
 *Not included in our scope of accreditation.

 Ken Ryeff
 Test Center Supervisor

PC 4.12.18F 1/5/09

There are no deviations from test methods herein noted. It is not intended to be assumed that mechanical properties of this material had treated to a further standard will have the same properties of a fabricator unless signed material characteristics may have been significantly altered.
 No recovery was indicated and no weld/repair was performed on this material while in the possession of TC Industries, Inc.
 This original test report displays a revised TC Industries Test Center seal. This test report remains only in the electronic and shall not be reproduced, except in full, without the written permission of TC Industries Test Center.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

FAX *** T C Industries - IL

REPUBLIC STEEL COMPANY, LLC.
ANCHOR BOLT & MFG. CO.
PO/Ref 96379

I hereby certify that this data is correct as contained in the records of this company.
I hereby certify that no money came in contact

Certificate of Mill Test Results
SO 1 - 183796-001
EJm09
Pg 1/2

with or no weld repair was done to this product
write in our possession.
Attn:



Republic
ENGINEERED PRODUCTS

3049 LAKESHORE-DAYS #
PHONE: 330-438-5694

BUFFALO, NY 14219
FAX: 330-438-5695

CERTIFICATE OF TESTS REPUBLIC ENGINEERED PRODUCTS February 27, 2009
PAGE 1

OF 2

PURCHASE ORD: 14885	PURCHASE ORDER DATE: 2/12/2009
PART NUMBER:	ACCOUNT NUMBER: 2645-1736-01
ORDER NUMBER: 1406104 - 01	SCHEDULE: 2102-68
DEPT: 6091874	REVISION: 1
SHIP TO:	SHIP TO:

<p>REPUBLIC STEEL COMPANY LLC 1550 N 30TH AVE MELROSE PARK, IL 60160</p>	<p>REPUBLIC STEEL COMPANY LLC MAIN C/O PITTSBURGH INTERNATIONAL 99 CENTURY DR AMBRIDGE, PA 15003</p>
--	--

MATERIAL DESCRIPTION

HOT ROLLED STEEL BARS ALLOY A572 GR50 ASTM A304-05 EP-AISI-4340-H FINE GRAIN VACUUM DEGAUSS
AIRCRAFT QUALITY RESTRICTED CHEMISTRY 8.00 | 1 RED BATED

SIZE: H28 8.0000" DIA X 20FT 0.0000" MIN/24FT 0.0000" MAX
H28 74.2000" DIA X 6094.0000" MIN/7115.2000" MAX

		LADLE CHEMISTRY &					
C	MF	P	S	SI	CU	NI	CR
0.48	0.74	0.009	0.005	0.24	0.19	1.68	0.80
V	NO	SN	AL	CB	N		
0.003	0.21	0.007	0.025	0.001	0.0076		

REDUCTION RATIO 18.4 TO 1
Standard Calculated Tests
P-S
EQUALS: 0.014

AUSTENITIC GRAIN SIZE 5 OR FINER BASED ON A TOTAL ALUMINUM CONTENT EQUAL TO OR GREATER THAN .020% PER ASTM A29.

SEMI - FINISHED RESULTS

LONGITUDINAL HARDNESS TEST SAE J408/ASTM A255

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
58	58	57	58	58	57	57	57	56	56	57	57	56	56	56	56	56	56	56	56	56	56	55	53	52	51	50	50				

MAGNETIC PARTICLE TEST AMS 2301 ANE1104 ANE2100

	END	AVG	END	AVG
	FREQ	FREQ	SEV	SEV
PCH 01	0	0	0	0

FINISHED SIZE RESULTS

MICROCLEANLINESS TEST ASTM 245 METHOD C SAE J432

	GAUGE	SILICATE
PCH 01	1	0

NOTES

REPUBLIC ENGINEERED PRODUCTS HEREBY CERTIFY THAT THE MATERIAL LISTED HEREIN HAS BEEN INSPECTED AND TESTED IN ACCORDANCE WITH THE METHODS SPECIFIED IN THE GOVERNING SPECIFICATIONS AND BASED UPON THE RESULTS OF SUCH INSPECTION AND TESTING HAS BEEN APPROVED FOR COMPLIANCE TO THE SPECIFICATIONS.

CERTIFICATE OF TESTS SHALL NOT BE REPRODUCED EXCEPT IN FULL.

ALL TESTING HAS BEEN PERFORMED USING THE CURRENT REVISION OF THE TESTING SPECIFICATIONS.

RECORDING OF FALSE, FICTITIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PENALIZED AS A FELONY UNDER FEDERAL STATUTE TITLE 18 CHAPTER 47.

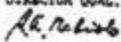
THE MATERIAL WAS NOT EXPOSED TO MERCURY OR ANY METAL ALLOY THAT IS LIQUID AT AMBIENT TEMPERATURE.

R. A. RESIDLO
DIRECTOR QUAL. ASSURANCE
BY KILDA DEBOE

R. A. Residlo

Doc No. E1083 Indexed 05Mar09 by clay

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

REPUBLIC STEEL COMPANY, LLC. AND BOLT & MFG. CO.		Certificate of Mill Test Results SO 1 -183796-001 2Jun09 Pg 2/2	
40UNCS A334RD WICKLAMPY T (S BARS) NO.		PO/Rel 94379 I hereby certify that this data is correct as contained in the records of this company. I hereby certify that no necessary action is required.	
		with or no weld repair was done to this product while in our possession. ADR:	
 Republic ENGINEERED PRODUCTS		3049 LAKEHURST-STATE 5 PHONE: 330-438-5694	
CERTIFICATE OF TESTS		SWEETEN, NE 14219 FAX: 330-438-5693 February 27, 2009 PAGE 1	
CP 2			
PURCHASE ORD: 18885. PART NUMBER: ORDER NUMBER: 1486304 - 01 HEAT: 8091870 DURING PROCESSING OR WHILE IN OUR POSSESSION.		PURCHASE ORDER DATE: 2/12/2009 ACCOUNT NUMBER: 5698-1730-01 SCHEDULE: 2102-68. REVISION: 1	
NO WELD OR WELD REPAIR WAS PERFORMED ON THIS MATERIAL.			
----- NOTES (CONTINUED) -----			
THE RESULTS REPORTED RELATE ONLY TO THE ITEMS TESTED			
----- SOURCE INFORMATION -----			
MELT SOURCE: CANTON CAST ROLL MELT METHOD: EP BLOOM END OF DATA		MELT COUNTRY: U.S.A RED. RATIO: 18.4 END OF DATA	
HOT ROLL SOURCE: LACKAWANNA 1316, U.S.A			
FAX - SHIP TO 1 COPY WITH SHIPMENT 2 COPIES FILE 1 COPY		ATTENTION 1-788-345-1734 PRINTED AT SHIPPING AREA	
E. A. WERTOLD DIRECTOR QUAL. ASSURANCE 		BY HILDA BROUS	
Doc No. 81981 Issued 6Mar09 by day			

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED MATERIAL TEST REPORT

 **DYSON CORP.**
DYN DOMESTIC NUT

RECEIVED
JUN 1 - 2009 440-946-3500
 440-352-2700 fax

53 Freedom Road
 Painesville, OH 44077

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 103320	96413	1 of 2	6 pcs	5/26/09

<p>CUSTOMER Portland Bolt & Manufacturing Co. Inc. PO Box 2866 Portland, OR 97208 USA</p>	<p>PRODUCT DESCRIPTION 3.00"-8UN-2B heavy hex nut</p> <p>SPECIFICATIONS ASTM-A194 Grade 2H</p>
--	--

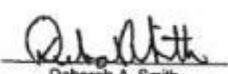
DRAWING
 Dyson Std

STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	3.250	1045	6	MSW3	M31730	Gerdau

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.

1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.
2. Hardness Results: 269/285 HBW 248 HBW after 24 hr. H.T. on sample nuts in accordance with ASTM-A194 Grade 2H

Attachments:
 Mill Test Report


 Deborah A. Smith
 Q.A. Admin, Assistant
 5/26/09

LARGE DIAMETER FASTENERS & FORGINGS / STANDARDS & SPECIALS / COMMERCIAL, MILITARY & NUCLEAR SPECIFICATIONS

Handwritten initials

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



ONE JACKSON SQUARE
SUITE 500
JACKSON, MICHIGAN 48201

CODE MSW3

CERTIFIED MATERIAL TEST REPORT

CUSTOMER ORDER NUMBER	CUSTOMER PART NUMBER	PSAT NUMBER	WORK ORDER NUMBER	DATE
26945	0	M31730	225458 101	12/10/08

REPORT TO
DAVE KRAUS
TURRET STEEL CORP.
LEETSDALE INDUSTRIAL PARK
FIRST STREET
P.O. BOX 55
LEETSDALE, PA 15056

SHIP TO
TURRET STEEL
PICK UP AT MILL

MONROE, MI

ORDERED

GRADE	SIZE	LENGTH
1045	3.25" RND	20'
CUSTOMER SPECIFICATIONS		
ASTM A322-07; A576-90B		

CHEMICAL ANALYSIS

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Sn	Al
0.46	0.73	0.014	0.024	0.25	0.07	0.13	0.02	0.17	0.016	0.003
V	Nb									
0.032	0.001									

GRAIN SIZE SPECIFICATION ASTM E112 FINE GRAIN 5-8

REDUCTION RATIO

RATIO- 4.3 TO 1.0

** MATERIAL 100% MELTED AND MANUFACTURED IN THE U.S.A. BY THE ELECTRIC ARC FURNACE AND CONTINUOUS CASTING METHOD. THE PRODUCT HAS NOT BEEN REPAIRED BY WELDING AND THIS MATERIAL HAS NOT BEEN EXPOSED TO MERCURY OR TO ANY OTHER METAL ALLOY THAT IS LIQUID AT AMBIENT TEMPERATURES DURING PROCESSING OR WHILE IN OUR POSSESSION. **

Q.A. REVIEWED
DATE 1/9/09
DYSON

PAGE 1 OF 1



MSW

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTIFIED MATERIAL TEST REPORT

 **DYSON CORP.**

RECEIVED

DYN DOMESTIC NUT

53 Freedom Road
Painesville, OH 44077

JUN 1 - 2009 440-946-3500
440-352-2700 fax

DYSON ORDER#	CUSTOMER ORDER#	ITEM NUMBER	QUANTITY SHIPPED	DATE SHIPPED
C 103321	96413	2 of 2	6 pcs	5/26/09

CUSTOMER
Portland Bolt & Manufacturing Co. Inc.
PO Box 2866
Portland, OR 97208
USA

PRODUCT DESCRIPTION
3.00"-8UN-2B heavy hex nut, HDG per ASTM-A153/
ASTM-F2329 & tapped .050" oversize with wax & dye

SPECIFICATIONS
ASTM-A194 Grade 2H

DRAWING
Dyson Std

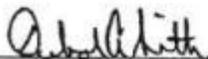
STARTING MATERIAL	DIA	GRADE	QTY	LOT CODE	HEAT NO.	ORIGINAL MILL
Round Bar	3.250	1045	6	MSW3	M31730	Gerdau

The product listed above was manufactured, tested, sampled, and inspected in accordance with the specification, purchase order, and any supplementary requirements and was found to meet those requirements unless otherwise noted.

1. The steel was melted and manufactured in the USA and the product was manufactured and tested in the USA.
2. Hardness Results: 269/285 HBW 248 HBW after 24 hr. H.T. on sample nuts in accordance with ASTM-A194 Grade 2H

Attachments:

Mill Test Report
Galvanizing Certification


Deborah A. Smith
Q.A. Admin. Assistant
5/26/09

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



ONE JACKSON SQUARE
SUITE 500
JACKSON, MICHIGAN 49201

CODE MSW3

CERTIFIED MATERIAL TEST REPORT

CUSTOMER ORDER NUMBER	CUSTOMER PART NUMBER	HEAT NUMBER	WORK ORDER NUMBER	DATE
26945	0	M31730	225458 101	12/10/08

REPORT TO
DAVE KRAUS
TURRET STEEL CORP.
LEETSDALE INDUSTRIAL PARK
FIRST STREET
P.O. BOX 55
LEETSDALE, PA 15056

SHIP TO
TURRET STEEL
PICK UP AT MILL
MONROE, MI

GRADE	SIZE	LENGTH
1045	3.25" RND	20'

CUSTOMER SPECIFICATIONS
ASTM A322-07; A576-90B

CHEMICAL ANALYSIS

C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Sn	Al
0.46	0.73	0.014	0.024	0.25	0.07	0.13	0.02	0.17	0.016	0.003
V	Nb									
0.032	0.001									

GRAIN SIZE SPECIFICATION ASTM E112 FINE GRAIN 5-8

REDUCTION RATIO

RATIO= 4.3 TO 1.0

** MATERIAL 100% MELTED AND MANUFACTURED IN THE U.S.A. BY THE ELECTRIC ARC FURNACE AND CONTINUOUS CASTING METHOD. THE PRODUCT HAS NOT BEEN REPAIRED BY WELDING AND THIS MATERIAL HAS NOT BEEN EXPOSED TO MERCURY OR TO ANY OTHER METAL ALLOY THAT IS LIQUID AT AMBIENT TEMPERATURES DURING PROCESSING OR WHILE IN OUR POSSESSION. **

Q.A. REVIEWED
DATE 1/8/09
DYSON

PAGE 1 OF 1

Gerda MacSteel Monroe
One Jackson Square
Suite 500
Jackson, Michigan 49201

Chris Easter

MSW

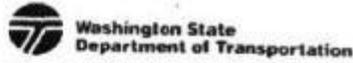
HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

CERTS

DATE	5/19/2009				
THE ART GALVANIZING WKS., INC.					
3935 VALLEY ROAD-CLEVELAND, OHIO 44109 PHONE 216-749-0020					
PACKING SLIP/CERTIFICATIONS					
TO	DYSON CORP.		PO#	66215	
NOTE:	THE FOLLOWING MATERIAL HAS BEEN HOT DIP GALVANIZED TO ASTM A 153 OR ASTM A 123 (LATEST REVISION) SPECIFICATION AS APPLICABLE. A COPY OF OF THE ABOVE PURCHASE ORDER IS AN INTERRAL PART OF THIS CERTIFICATION AND SHOULD BE ATTACHED.				
72 PCS MISC. WASHERS		7 PCS 3" HHN CODE MSW-3		53 PCS 3" HHN CODE MSW-3	
GALV WEIGHT		95#	GALV WEIGHT		66#
INCHES	OZ/SQ FT		INCHES	OZ/SQ FT	502#
0.0038	2.24		0.0058	3.41	0.0028
0.0046	2.71		0.0064	3.76	0.0038
0.0042	2.47		0.0052	3.06	0.0038
0.0034	2.00		0.0066	3.88	0.0042
0.0048	2.82		0.0074	4.35	0.0046
AVG	2.45		AVG	3.69	AVG
					2.24
GALV WEIGHT		GALV WEIGHT		GALV WEIGHT	
INCHES	OZ/SQ FT	INCHES	OZ/SQ FT	INCHES	OZ/SQ FT
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
AVG	0.00	AVG	0.00	AVG	0.00
GALV WEIGHT		GALV WEIGHT		GALV WEIGHT	
INCHES	OZ/SQ FT	INCHES	OZ/SQ FT	INCHES	OZ/SQ FT
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
0	0.00	0	0.00	0	0.00
AVG	0.00	AVG	0.00	AVG	0.00

Page 1 *M. J. [Signature]*

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts



Request for Approval of Material

Contract **C6525** FA Number **BR-0104(25)** SR **104** Date _____
 Section **MP 13.75 TO MP 15.50** County **KITSAP & JEFFERSON**
 Contractor **KIEWIT-GENERAL, JV** Subcontractor **Suppliers PORTLAND BOLT & GALVANIZERS COMPANY**

For assistance in completing, see instructions and Example

For WSDOT Use Only
RAM # 1332T

Big Item No.	Material or Manufacturer's Product/Type	Name and Location of Fabricator, Manufacturer or Pt Number	Specification Reference	PE Appl Code	Hdqr. Appl Code	File No
162	3" X 24" ASTM A354 BD ROD w/ NUTS • GALV & BLACK	PORTLAND BOLT PORTLAND, OR	RFI-1316	7	2,6	
	• GALVANIZING OF RODS	GALVANIZERS COMPANY PORTLAND, OR	• RFI-1316		2	

* RFI 1316 - SEE ATTACHED SUMMARY PAGE.

Project Engineer **AG** Date **08/12/2009** State Materials Engineer **Chris Robert** Date **6/12/09**

- Approval Action Codes for use by Project Engineers and State Materials Laboratory**
- Conditionally Approved: Acceptance based upon 'Satisfactory' Test Report for samples of materials to be incorporated into project
 - Conditionally Approved: Submit Mfg. Cert. of Compliance for 'Approval' prior to use of material
 - Conditionally Approved: Submit Catalog Cuts for 'Approval' prior to use of material
 - Conditionally Approved: Submit Shop Drawings for 'Approval' prior to fabrication of material
 - Conditionally Approved: Only 'Approved for Shipment' or 'WSDOT Inspected' material shall be used
 - Conditionally Approved: Submit Materials Certificate of Origin to Project Engineer
 - Approval Pending: Request Transmitted to State Materials Laboratory for Approval Action
 - Source Approved
 - Approval Withheld: Submit samples for preliminary evaluation
 - Approval Withheld
 - Remarks
- Sent / Fax to Contractor: 08/12/2009
- Submittal No. C05318.02.041
- 6/12/09 - WSDOT TO VERIFY IF INSPECTION REQUIRED/DESIRED.

Project Engineer Distribution
 Contractor Region Materials State Materials Lib M.S 4/765
 Region Operations Engineer

State Materials Engineer Distribution
 General File Signing Inspection Other
 Fabrication Inspection

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

APPENDIX E

**Dwight Co Welding Laboratory Service
Failure Analysis Report**

DRAFT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

DWIGHT COMPANY, Inc.
WELDING LABORATORY SERVICE

414 HEWITT RD, CHEHALIS, WA., 98532; 360-262- 9844, FAX 360-262-9404, e-mail: dwright@weidlab.com



www.weidlab.com

Mayes Testing Engineers	Date :	Sunday, April 26, 2009
22025 Cedar Valley Road, Suite 110		
Lynnwood, WA. 98036		
Attention: Mr. Mike Mayes P.E., & Mr. Geoff Swett P.E., Mr. Scott Ireland, P.E.	Fax:	

Metallurgical Record of FW 3" Bolt Failures on East Half - 2009

BACKGROUND:

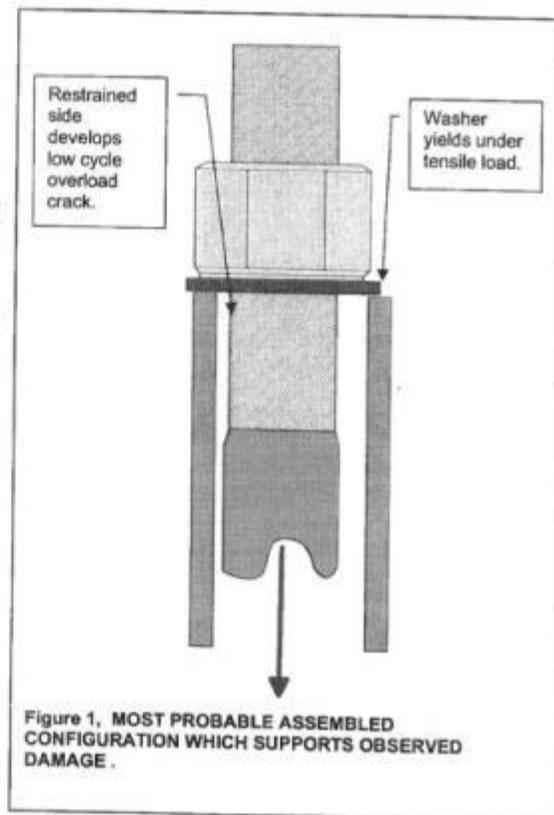
Figure 1 shows the most probable bolt loading assembled condition.

The damaged washer components show that a significant off center condition existed when the 3" diameter nuts were tightened against the larger housing tube / washer combination.

The microstructures examined in bolt threaded areas #5 & #8 are located in close proximity to the fracture surfaces.

OBJECTIVES OF TEST WORK:

1. To determine the probable failure cause.
2. To determine if hydrogen damage is present in the failed bolts at fracture interface.
3. To provide specific fracture surface records and microphoto section data.
4. To suggest inspection details for corrective action.



HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

SPECIMENS RECEIVED FOR ANALYSIS:

Two (2) failed 3" diameter bolts , nuts and washers are shown in Figures 2, and 3.

The fracture surfaces are clearly visible and are covered with a light patina of iron oxide (rust).

INITIAL LOW CYCLE CRACK

Both fractures are reported to have occurred as part of a routine tensile torque procedure.

Engineers advise that there are 14 of the 3" diameter bolt , nut and washer assemblies.

To date, three (3) of the fourteen (14) have failed.

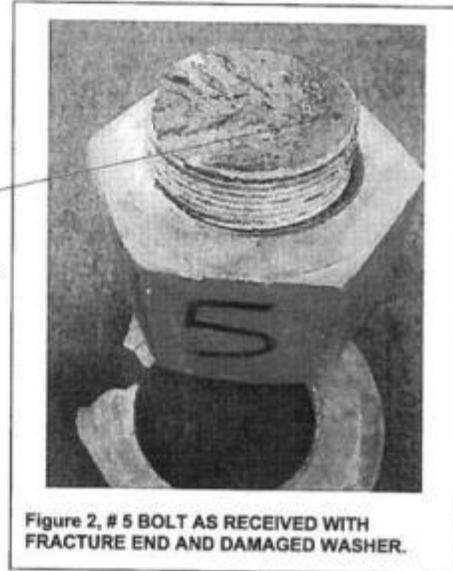


Figure 2, # 5 BOLT AS RECEIVED WITH FRACTURE END AND DAMAGED WASHER.

FRACTURE MORPHOLOGY

Both fracture surfaces show an initial crack start region with a large fast fracture area.

FINAL FAST FRACTURE REGION (typical of both bolt assemblies)

INITIAL LOW CYCLE CRACK

This condition was found on both the failed bolt assemblies.

The washers on both assemblies were also heavily damaged, Both washers showed significant deformation from compressive stress.

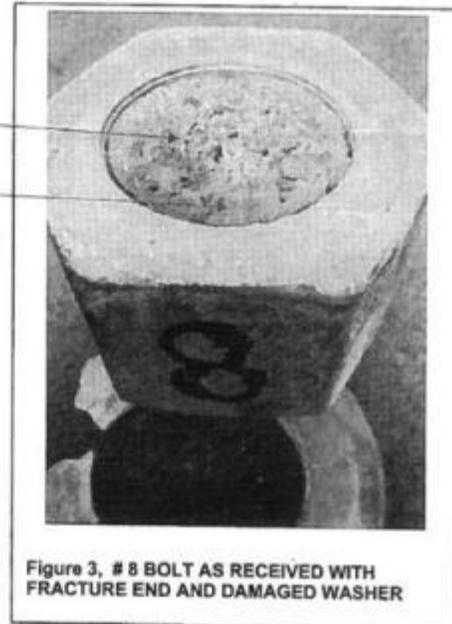


Figure 3, # 8 BOLT AS RECEIVED WITH FRACTURE END AND DAMAGED WASHER

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

MICROSTRUCTURE RECORD 3" DIAMETER # 5 BOLT ASSEMBLY

The thread root micro is typical for an overload tensile adjacent to the fracture surface.

The crack at the root is not hydrogen induced.

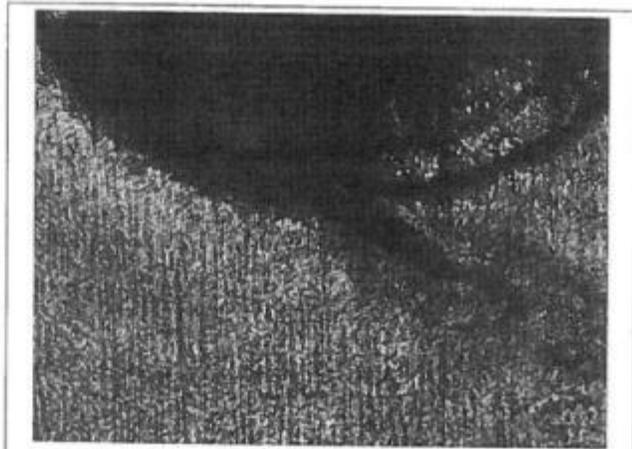


Figure 4, 100X MICROPHOTO OF #5 IN THREAD ROOT WITH TEARING AT THE ROOT.

The microphoto in Figure 5 is located at the crack start region.

There are small tears at the surface but no evidence of hydrogen damage.

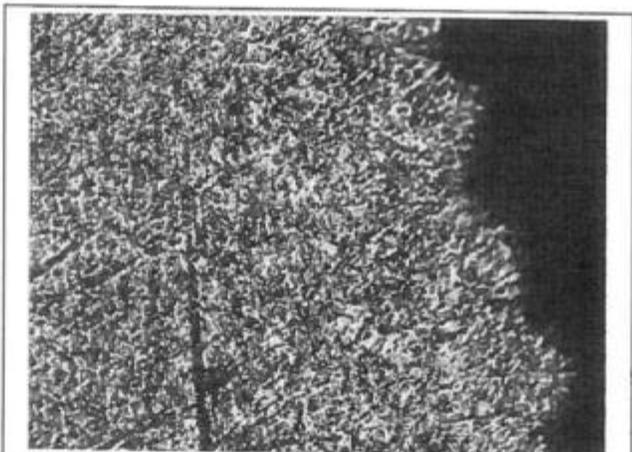


Figure 5, 400X MICROPHOTO OF THE CYCLIC CRACK START REGION OF BOLT #5.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

The microphoto in Figure 6 is located at the start of the fast fracture region.

Again there is no evidence of hydrogen damage.

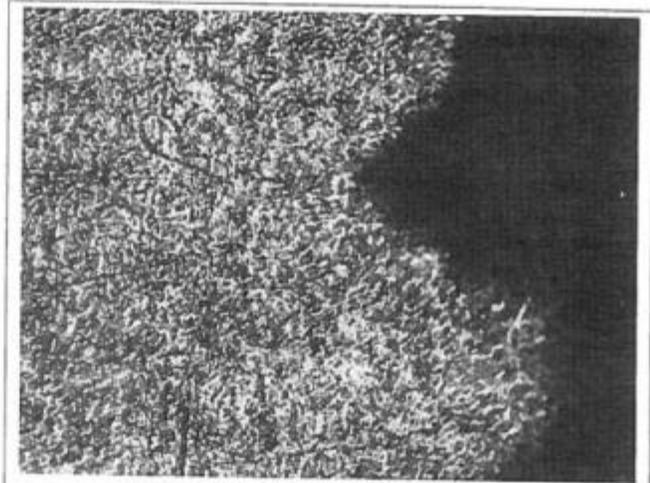


Figure 6, 400X MICROPHOTO OF THE FAST FAILURE REGION OF BOLT #5

MICROSTRUCTURE RECORD 3" DIAMETER # 8 BOLT ASSEMBLY

The thread root micro does not show any overload tensile damage adjacent to the fracture surface.

Hydrogen induced damage is not visible at the root .

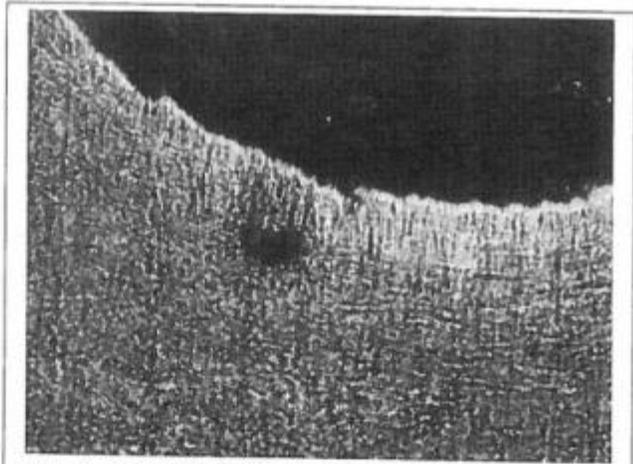


Figure 7, 100X MICROPHOTO OF #8 BOLT IN THREAD ROOT. THERE IS ONE SMALL NON-METALLIC INCLUSION AT THE ROOT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

MICROSTRUCTURE RECORD 3" DIAMETER # 8 BOLT ASSEMBLY, continued

The microphoto in Figure 8 is located at the crack start region.

There are no small tears at the surface and no evidence of hydrogen damage.

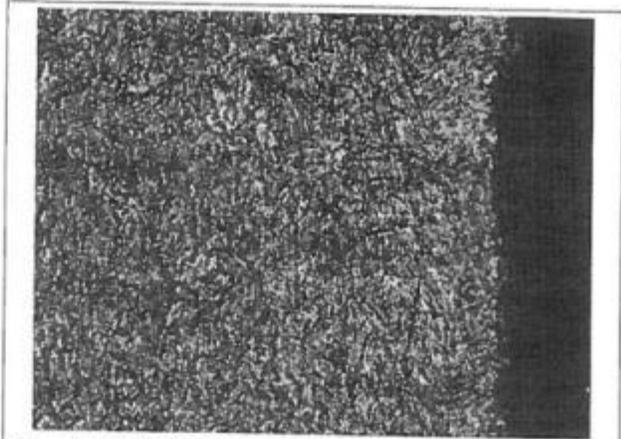


Figure 8, 400X MICROPHOTO OF THE CYCLIC CRACK START REGION OF BOLT #8.

The microphoto in Figure 9 is located at the start of the fast fracture region.

Again there is no evidence of hydrogen damage.

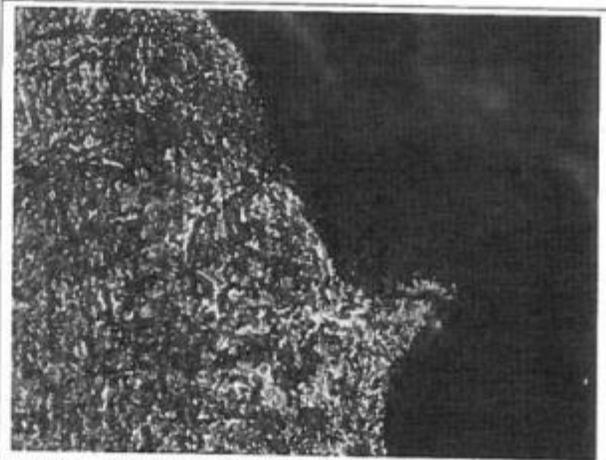


Figure 9, 400X MICROPHOTO OF THE FAST FAILURE REGION OF BOLT #8.

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

INSPECTION DETAIL RECOMMENDATIONS

The material microstructures are tempered martensite and pearlite with some ferrite. This microstructure will be sensitive to off center loading at thread roots as is the case in the examples examined on failed bolts 5 & 8.

The following is recommended to determine the actual surface condition and probable volume condition of each 3" diameter bolt that has been loaded.

1. Unload all bolts.
2. Clean / degrease the complete thread surface to a smooth or bright metal condition.
3. Use a very sensitive PT method to perform and initial screening of the entire thread surface.
4. Follow up with an MT or UT as recommended by the NDE engineers.
5. Accept or reject each bolt by serial number.
6. Replace bolts with crack like indications.
7. Use high strength step washers with the 3" diameter bolts to assure a concentric fit-up.
8. Re-torque in accordance with the drawing procedure.

SUMMARY OF FINDINGS

- o The probable failure cause of the 3" bolt assemblies is non-concentric loading during the final torque tensioning.
- o Hydrogen damage was not present in the failed bolts at fracture interface or adjacent to the fracture area.
- o Inspection details for corrective action have been suggested based on the metallurgy observed in this brief investigation.

Notarized if Required

J. M. Dwight
Signature

Welding Engineer
Title

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

DRAFT

APPENDIX F

Lisin Metallurgical Services Failure Analysis - Report 1

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

September 13, 2013

Bainbridge Structures Group
Attn: Robert Shulock, PE
13908 Sunrise Dr. NE
Bainbridge Island, WA 98110
E-mail: rshulock@BainbridgeStructures.com



Subject: Analysis of Two Failed ASTM A354 Grade BD 3 Inch Diameter Galvanized Steel Bolts
Lisin Metallurgical Services Job No. 524-13-001

Dear Bob,

Fracture initiation in two failed 3 inch diameter ASTM A 354 Grade BD high strength galvanized steel bolts was the result of hydrogen embrittlement. *Hydrogen embrittlement* refers to a loss of strength and ductility in some high strength alloys upon sustained tensile loading due to absorption of as little as a few ppm of hydrogen. Evidence of hydrogen embrittlement includes the reported delayed failure within an estimated 2 weeks of load application and the presence of a partially intergranular fracture initiation.

Five likely contributing factors to hydrogen embrittlement failure were identified:

- 1) A high specified installation stress of 70% of the minimum specified ultimate tensile strength.
- 2) A likely increase in tensile stress due to washer deformation and a resulting superimposed bending load. Evidence of a superimposed bending load included severely deformed and cracked washers and fracture initiation on one side of the bolt and propagation to final overload on the opposite side. Multiple thread root cracks in adjacent threads on the fracture initiation side of the bolt but not on the final failure side of the bolt further suggests application of a superimposed bending load.
- 3) Use of a galvanized coating:
 - a. Pre-galvanizing surface preparation by acid pickling can introduce hydrogen.
 - b. Corrosion of the galvanized coating can result in formation of hydrogen at coating holidays (areas of bare steel). The source of hydrogen (steelmaking, pickling, corrosion) has not (and can not) be identified with certainty.
- 4) Minor corrosion of both the galvanized coating and the steel substrate was apparent, and the corrodant chlorine was detected in corrosion product deposits. Hydrogen generation is possible under these conditions.
- 5) A marginal microstructure and limited fracture toughness resulting from selection of a "lean" alloy for this large diameter bolt. Specifically, some transformation products other than the desired tempered martensite were present in the bolt alloy.

Final overload fracture occurred in a brittle manner. Brittle rather than ductile overload was promoted by a less than optimum microstructure, a sharp crack tip present in

Specializing In Failure Analysis

2335 SE Harrison, Milwaukie, Oregon 97222 Ph. (503) 657-0557 Fax (503) 657-6207 Mark@lisinmet.com

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a thick section, and application of high tensile stresses. A large area of final overload relative to the fracture initiation attests to the high tensile stresses present within the bolt.

The measured alloy composition and tensile properties of duplicate bars removed from a mid-radius location of one bolt met the requirements of Grade BD of ASTM A 354. Hardness measurements at a mid-radius location were below specification requirements. However, tensile properties take precedence over hardness and the bolt material is considered to be within the specified requirements of ASTM A 354.

Inspection of the galvanized coating revealed evidence of both mechanical damage, likely due to nut installation, and minor corrosion. Some areas of bare steel were apparent.

Introduction:

Two previously sectioned and analyzed bolts were received for analysis. The bolts were reportedly specified as 3 inch diameter, galvanized steel bolts per Grade BD of ASTM A 354. These two failed bolts were reportedly discovered by a painting crew on April 24th, 2009 within an estimated 14 days after installation. Installation reportedly resulted in an axial tensile stress of 70% of the minimum specified ultimate tensile strength of 140 ksi per Grade BD. There were 12 bolts installed from a lot of 20 bolts manufactured by Dyson Corp. A third bolt failed later in the day on the 24th April and three more reportedly fractured completely within the next week. Visual inspection of the six remaining intact bolts confirmed that all showed indications of permanent deformation and they were rejected. Bolts were reportedly installed with washers that were too thin for the annular space between the bolt and the CIP 4 inch diameter pipe sleeves.

Our analysis initiated with visual inspection of the bolts. Selected locations of the fracture surfaces were further evaluated by optical and scanning electron microscopy. Deposits on the bolts (likely contaminated) and the washers (likely uncontaminated) were analyzed by energy dispersive x-ray spectroscopy. Alloy composition was characterized by optical emission spectroscopy. Samples were removed from one bolt for tensile testing and Charpy impact testing. A Rockwell hardness survey was completed on one bolt, and Vickers 300 gram microhardness surveys were completed on both bolts. Metallographic examination of longitudinal-radial sections through the fracture initiation sites, location of final fracture, and threads was also performed. The condition of the galvanized coating was qualitatively assessed by optical and scanning electron microscopy and metallographic examination.

Detailed results of the analysis are documented in the following tables and figures. Thank you for working with Lisin Metallurgical Services on this project. Please feel free to contact us with any comments or questions about these results.

Sincerely,



Mark A. Lisin, P.E.
Lisin Metallurgical Services

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**Table 1
Work Scope**

Analysis	Description	Bolt #5	Bolt #8
Visual inspection	Document any corrosion, deformation, thread damage, galvanizing damage, etc.	X	
Optical fractography	Identify location of fracture initiation, final overload fracture.	X	X
Scanning electron microscope fractography	Determine the failure mode, and specifically, determine if fracture initiation was the result of hydrogen embrittlement. Document overload fracture mode.	X	X
Energy dispersive x-ray spectroscopy	Determine the composition of any corrodants (e.g. chloride).	X	
Optical emission spectroscopy	Determine alloy composition. Determine conformance to specification.	X	
Tensile testing	Determine mechanical properties. Determine conformance to specification.	X	
Charpy impact testing	Characterize the impact toughness at -20 °F.	X	
Microhardness testing	Identify any carburization or decarburization. Determine conformance to specification.	X	X
Metallographic examination	Characterize alloy cleanliness and quality. Characterize heat treatment. Identify any carburization or decarburization. Document intergranular or transgranular crack path. Characterize zinc and steel cracking at initiation side and opposite side thread roots.	X	X
Scanning electron microscope examination of threads away from fracture	Document the extent of degradation of the galvanized coating.	X	

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Table 2
Measured Tensile Properties of Two Test Bars removed from Bolt 5 and the Requirements of ASTM A 354 Grade BD

Sample Identification	Ultimate Tensile Strength, ksi	Yield Strength, ksi	% Elongation in 4D	% Reduction of Area	Original Gage Diameter (inch)
Measured, 1	153.0	131.3	17.0	54.5	0.352
Measured, 2	152.5	133.0	17.0	55.5	0.350
Requirements of ASTM A 354 Grade BD	140.0 Min.	115.0 Min.	14 Min.	40 Min.	---

Duplicate tensile test bars were removed from an approximate mid-radius section of Bolt 5. The measured tensile properties meet the specified requirements of ASTM A 354 Grade BD.

Table 3
Measured -20 °F Charpy Impact Energy of Three Test Bars removed from Bolt 5

Sample Identification	Size (mm)	Ft.-Lbs.
Measured, 1	10 X 10	≈6.0
Measured, 2	10 X 10	≈10.0
Measured, 3	10 X 10	≈12.0
Average	---	≈9.5

Charpy impact testing is not a requirement of ASTM A 354. Testing was performed at the request of the customer. No specification or requirement was provided. The low impact energy values are consistent with the observed brittle overload fracture and the mixed microstructure of tempered martensite and other transformation products. A more hardenable material such as Grade 4340, properly heat treated to a similar hardness, would likely exhibit substantially higher Charpy impact energies.

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Table 2
Measured Alloy Chemistry, Bolt 5 and the Requirements of ASTM A 354 Grade BD

Element	Weight Percent	
	Measured, Bolt 5	Requirements of ASTM A 354 Grade BD
Carbon	0.42	0.35-0.55
Manganese	0.90	0.57 Minimum
Phosphorus	0.015	0.045 Maximum
Sulfur	0.022	0.045 Maximum
Boron	0.0005	0.0005-0.003
Silicon	0.21	---
Chromium	0.94	---
Nickel	0.10	---
Molybdenum	0.18	---
Aluminum	0.01	---
Copper	0.25	---
Niobium	<0.01	---
Titanium	<0.01	---
Vanadium	0.008	---
Iron	Balance	Balance

The measured alloy chemistry meets the specified requirements of ASTM A 354 Grade BD. The alloy composition is characteristic of a Grade 4140 or similar alloy steel.

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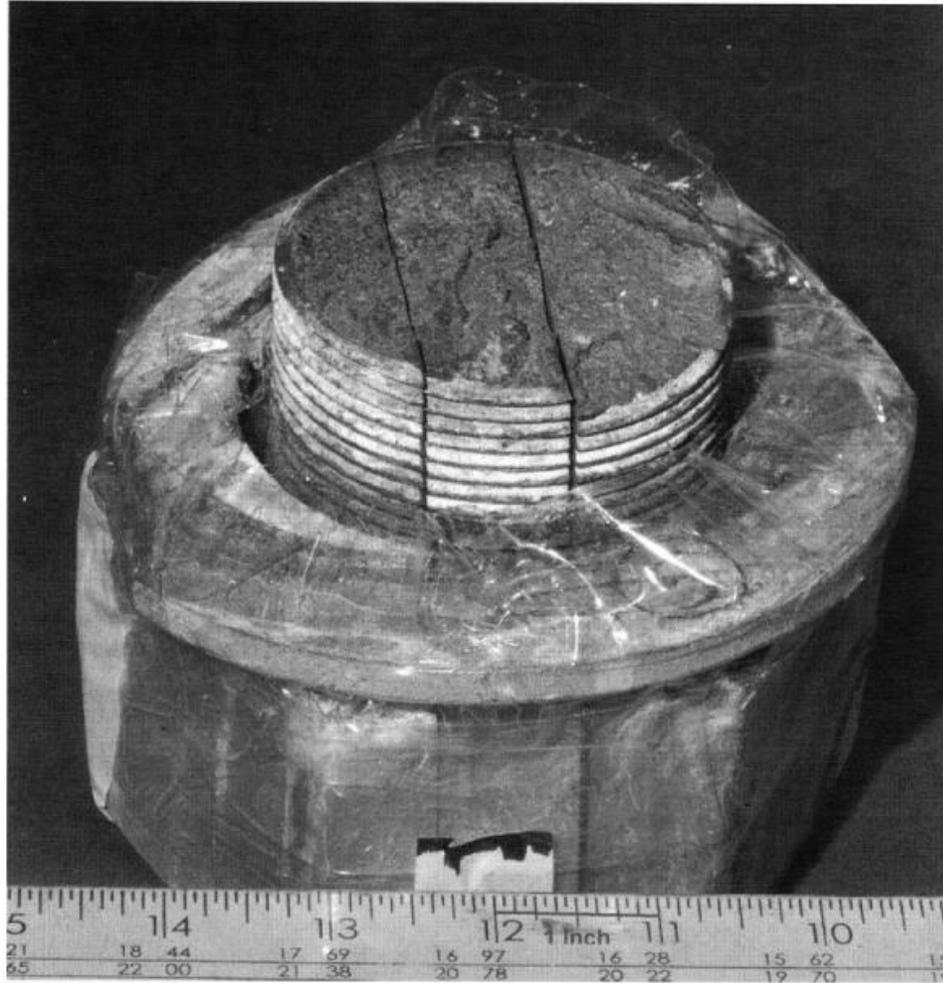


Figure 1

Sample 5 in the as-received condition. The sample consisted of a previously sectioned bolt, nut, and washer. The sample had been reassembled and wrapped in clear adhesive tape to retain the various remnants. The bolt was approximately 4 1/4 inches long by 3 inches in diameter. The fracture surface exhibited superficial rusting, and some non-uniform accumulation of white deposit suggests that some corrosion of the apparent galvanized surface had occurred. The washer was deformed well outside of the original plane and contained multiple fractures and cracks. The scale divisions at the bottom of the photograph are 1/16 inch.

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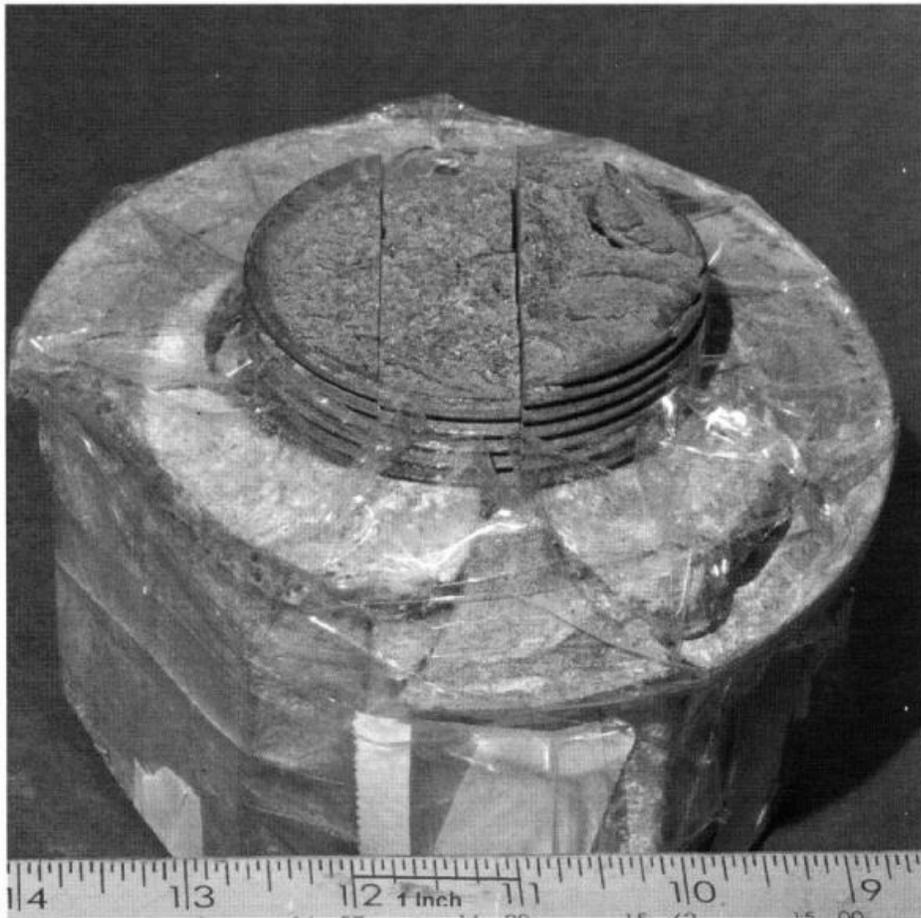


Figure 2

Sample 8 in the as-received condition. The sample consisted of a previously sectioned bolt, nut, and washer. The sample had been reassembled and wrapped in clear adhesive tape to retain the various remnants. The bolt was approximately 4 1/4 inches long by 3 inches in diameter. The fracture surface exhibited superficial rusting, and some non-uniform accumulation of white deposit suggests that some corrosion of the apparent galvanized surface had occurred. The washer was deformed well outside of the original plane and contained multiple fractures and cracks. The geometry, fracture location, and apparent failure mechanism of Bolts 5 and 8 appeared to be essentially identical based on visual examination. The scale divisions at the bottom of the photograph are 1/16 inch.

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Figure 3

Sample 5 fracture surface. Ridges and grooves on the fracture point to an apparent fracture initiation area within the green oval. An abrupt boundary between smooth fracture at the initiation area and rough fracture over the majority remainder of the fracture indicates fracture in two stages or steps and likely due to two different fracture mechanisms. The rough fracture is characteristic of brittle final overload. The large area of final overload relative to the initiation fracture mode is indicative of a large stress magnitude. Fracture was oriented transverse to the axis of the bolt. Transverse brittle fracture is indicative of an axial tensile stress. Fracture was not the result of torsional overload. The scale divisions at the bottom of the photograph are 1/16 inch.

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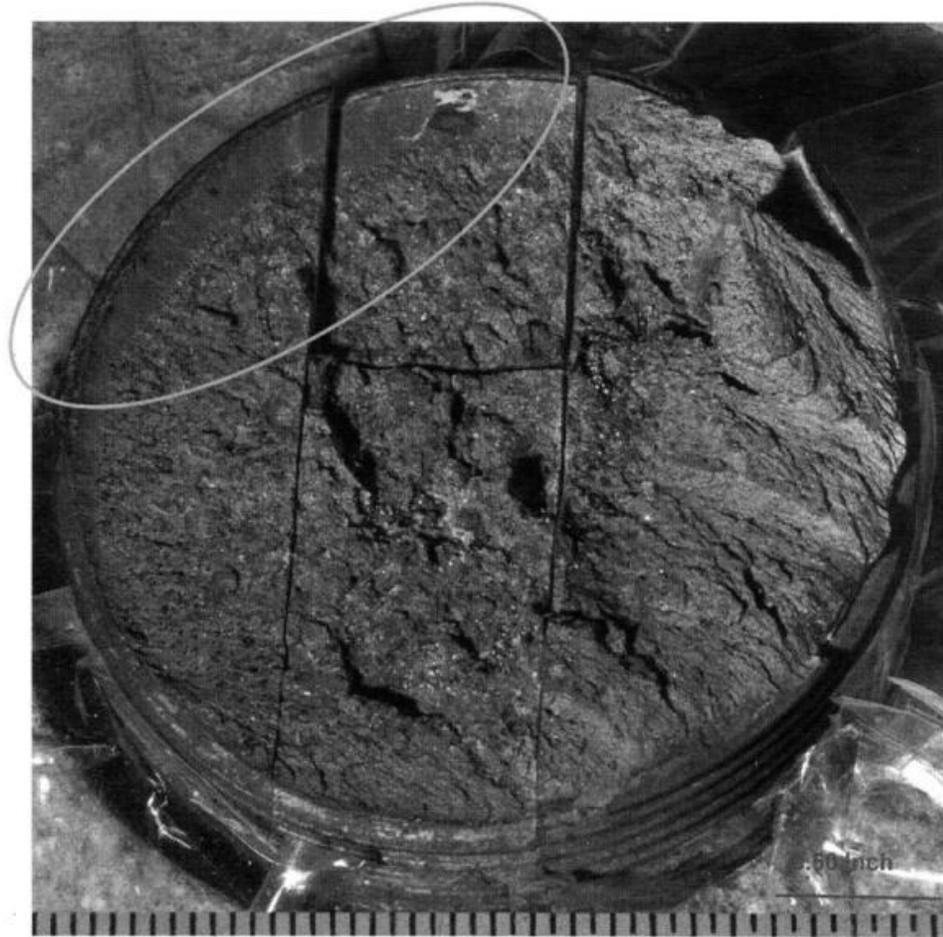


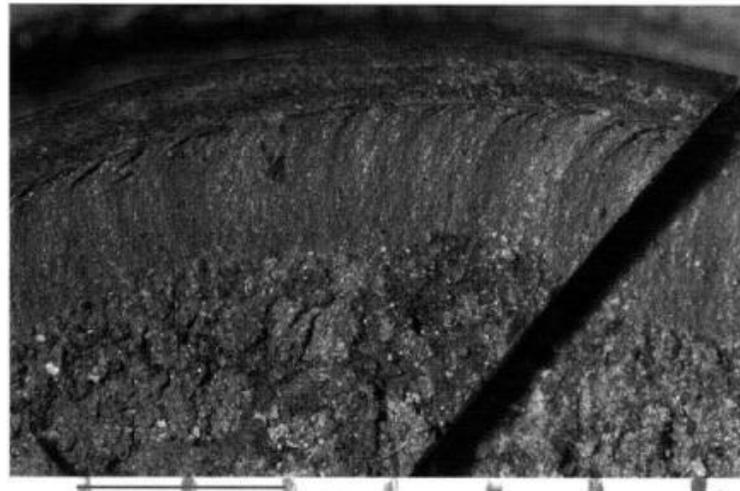
Figure 4

Sample 8 fracture surface. Ridges and grooves on the fracture point to an apparent fracture initiation area within the green oval. An abrupt boundary between smooth fracture at the initiation area and rough fracture over the majority remainder of the fracture indicates fracture in two stages or steps and likely due to two different fracture mechanisms. The rough fracture is characteristic of brittle final overload. The large area of final overload relative to the initiation fracture mode is indicative of a large stress magnitude. Fracture was oriented transverse to the axis of the bolt. Transverse brittle fracture is indicative of an axial tensile stress. Fracture was not the result of torsional overload. The initial fracture closely followed the thread root and the circumference of the bolt. Preferential fracture along the thread root indicates that the thread root acted as a substantial stress concentration. The scale divisions at the bottom of the photograph are 1/16 inch.

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Bolt #5, X



Bolt #8, X

Figure 5

Apparent fracture initiation regions of Bolts 5 and 8. Faint ridges point to fracture initiation at the root of the thread of Bolt 5. Arc shaped features on the fracture surface just below the thread root may indicate deformation due to thread rolling. The scale divisions at the bottom of the photograph are 1/16 inch.

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Figure 6

Washer from Bolt 8 in the as-received condition. Substantial axial deformation and fracture was apparent on both washers. We understand that the washers were too thin for the annular space between the bolt and the CIP 4 inch diameter pipe sleeves and that failure at the specified bolt loads would predictably cause washer failure. The observed deformation of the washer would predictably result in non-uniform bearing loads against the face of the mating nut. As a result, a bending load could exist in the bolt. The scale divisions at the bottom of the photographs are 1/16 inch.

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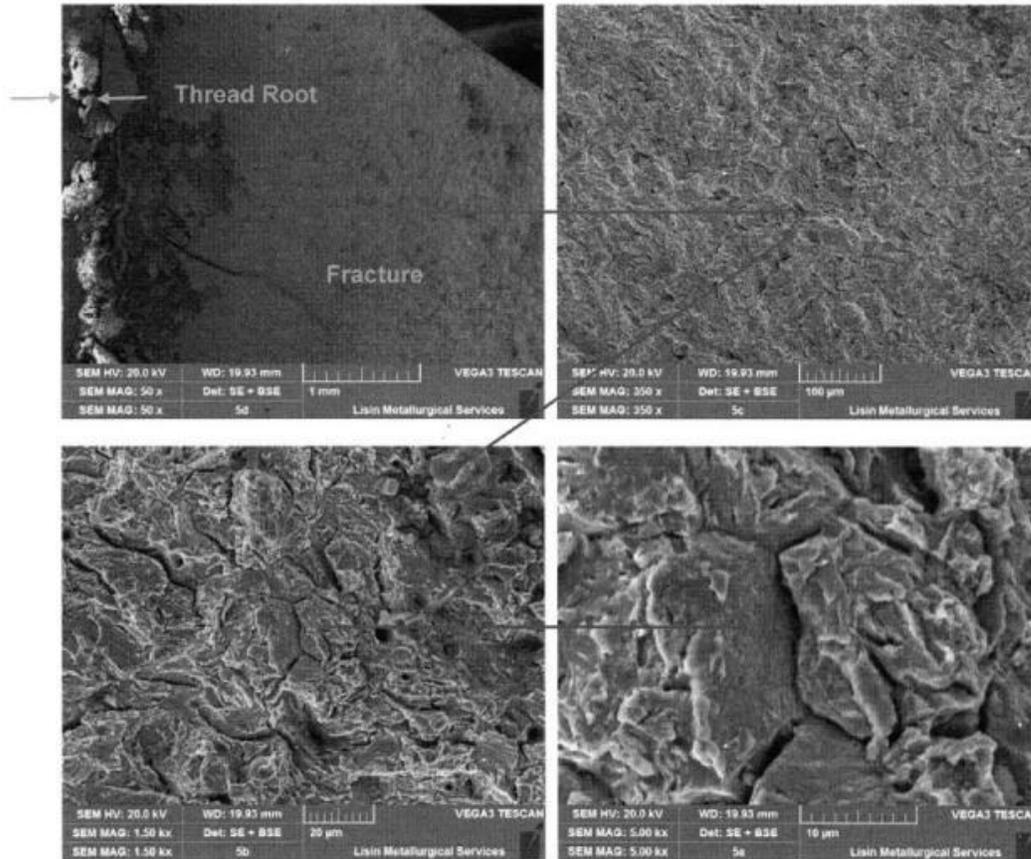


Figure 8

Mixed backscattered and secondary electron images acquired from the fracture surface of Bolt 5. The location shown is approximately 1 to 2 mm below the thread root, within the crescent shaped band of smoother fracture near the fracture initiation. This location is likely below the heavily deformed material created during thread rolling. Partially intergranular fracture along more equiaxed prior austenite grain boundaries is apparent. The fracture surface again appears to consist of a mix of brittle intergranular fracture and ductile or partially ductile transgranular fracture. Intergranular fracture is one characteristic of hydrogen embrittlement.

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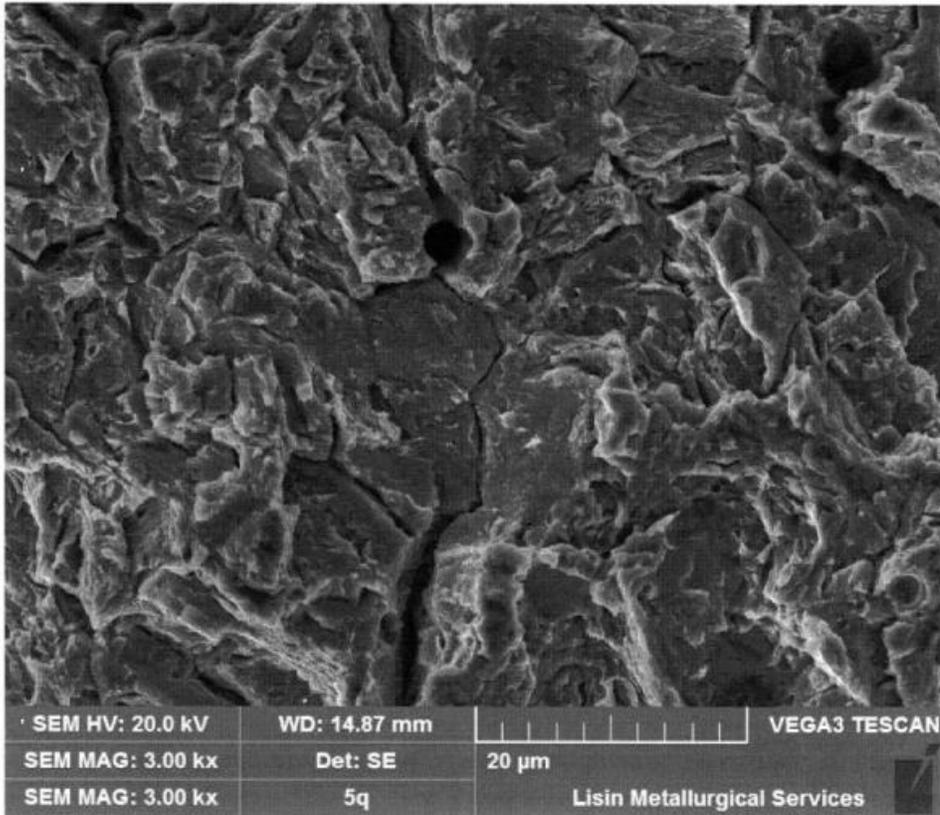


Figure 9

Secondary electron image acquired from the fracture surface of Bolt 5. The location shown is approximately 1 to 2 mm below the thread root, within the crescent shaped band of smoother fracture near the fracture initiation. The location shown is the most pronounced example of intergranular fracture revealed by an extensive search. The fracture surface at this location again consists of a mix of brittle intergranular fracture and more ductile transgranular fracture. Severe hydrogen embrittlement or hardened alloy steels, likely due to high hydrogen levels or high hardness levels typically exhibits pronounced intergranular facets and little or no ductile fracture. The mix of both ductile and brittle intergranular fracture suggests that fracture was due to embrittlement on the less severe side of a mild embrittlement to severe embrittlement continuum.

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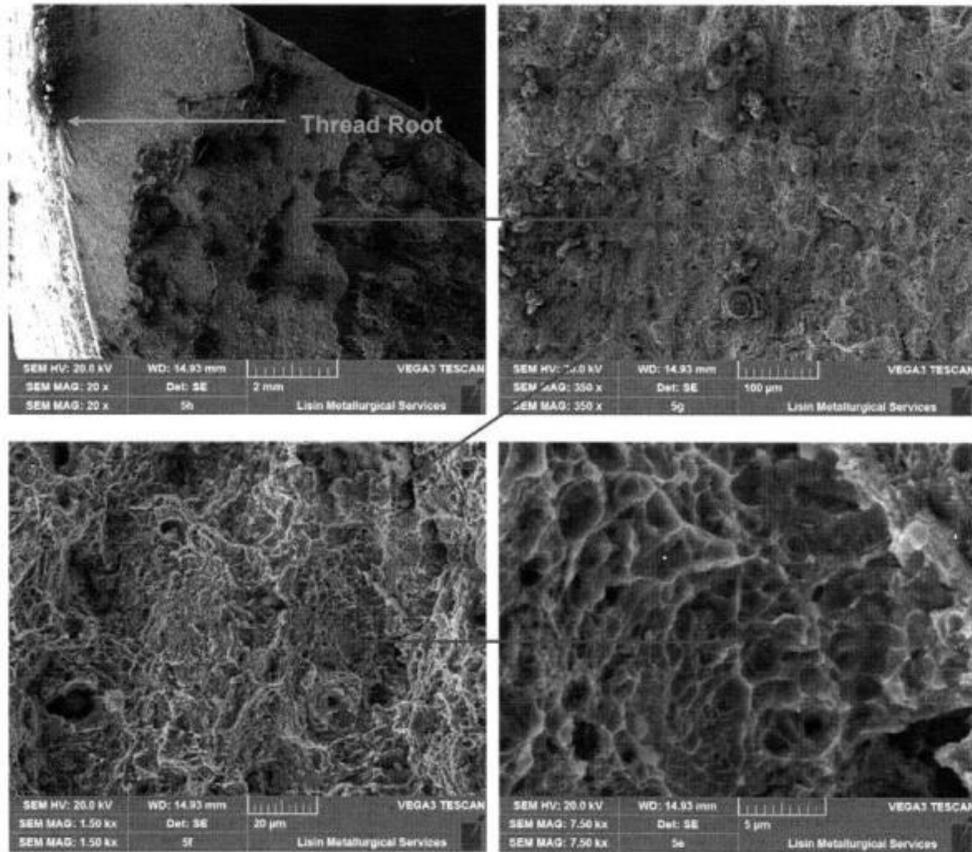


Figure 10

Secondary electron images acquired from the fracture surface of Bolt 5. The location shown is at the boundary between smooth fracture initiation and rougher overload fracture. The fracture surface features consist of micro-void coalescence (MVC). MVC is a ductile, transgranular fracture mode. Alternate bands of intergranular fracture and MVC can exist when hydrogen migrates to a crack tip and embrittles a local area at the tip of the crack. Crack extension due to this local embrittlement can result in crack propagation outside of the hydrogen rich zone and into ductile material. The presence of ductile overload argues against failure due to an inherently brittle material such as would occur with temper embrittlement. The ductile fracture suggests failure due to a localized or transitory mechanism such as hydrogen embrittlement.

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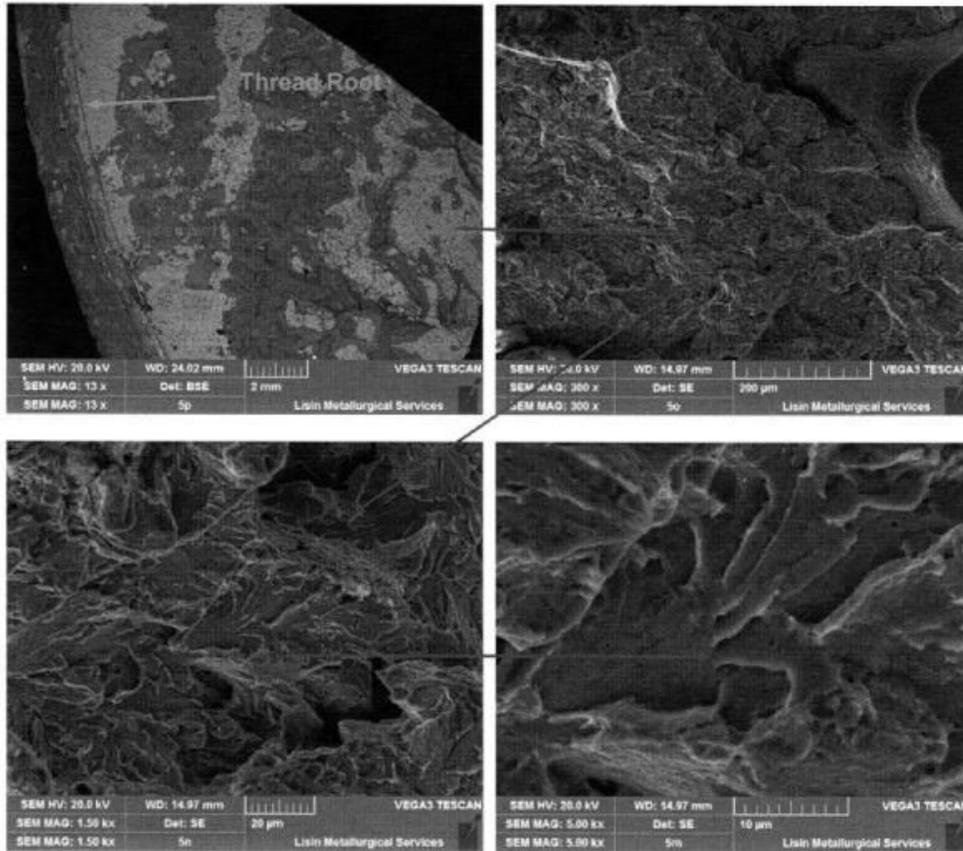


Figure 11

Secondary electron images acquired from the fracture surface of Bolt 5. The location shown is within the rougher overload fracture. Fracture was the result of brittle transgranular cleavage. Cleavage fracture can result from limited ductility, thick sections, and severe stress concentrations such as a crack tip. Cleavage is not characteristic of hydrogen embrittlement. The limited amount or small zone of intergranular fracture again suggests a "mild" case of embrittlement in the mild to severe embrittlement continuum.

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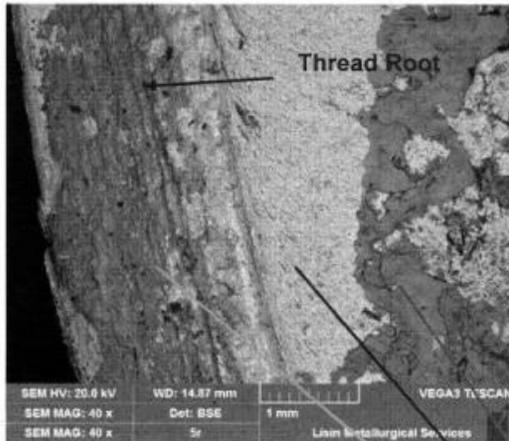
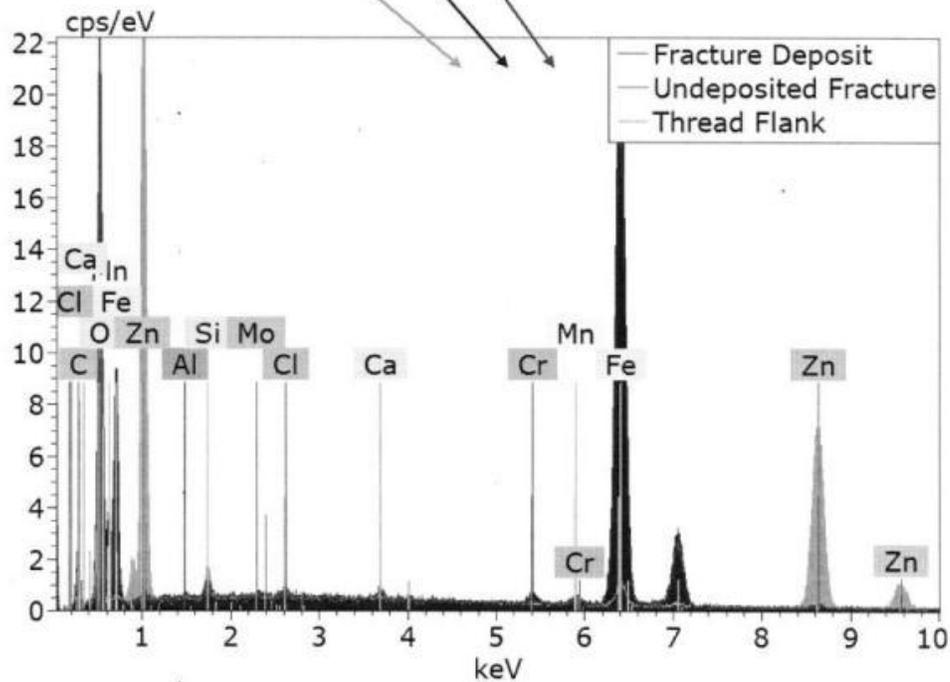


Figure 12 Backscattered electron image and energy dispersive x-ray spectra acquired from the fracture surface near the fracture initiation site, Bolt 5. The bolt fracture had been coated with lacquer when received by the laboratory, and the fracture surface was therefore ultrasonically cleaned in organic solvents and a mild alkaline cleaner prior to the analysis. Fracture surface deposits consisted primarily of iron oxide. Zinc on the threads is consistent with a galvanized surface. The alloy composition is consistent with an alloy steel such as Grade 4140 or similar.



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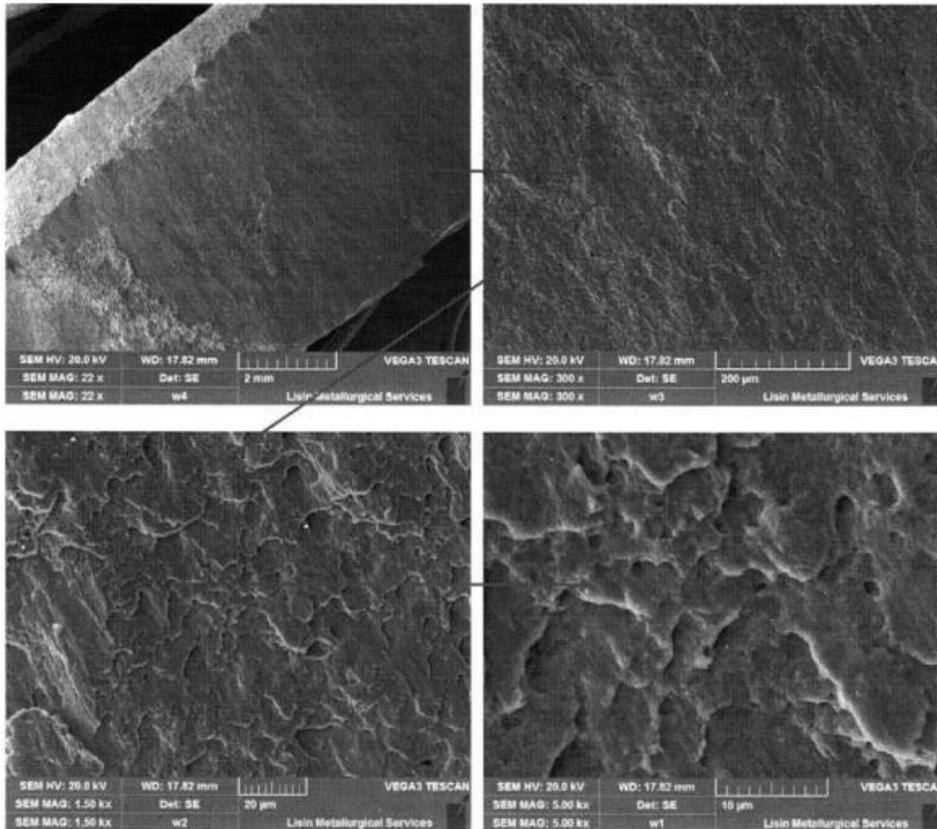


Figure 13

Secondary electron images acquired from a representative fracture surface on the Bolt 5 washer. The features are consistent with ductile shear fracture. The macroscopic deformation and shear fracture of the washer indicate that the washer thickness or strength was simply insufficient to support the clamp loads, and the fracture deformed into the hole and eventually fractured. Deformation and fracture of the washer could lead to non-uniform bearing on the nut and off axis loading on the bolt. We understand that the bolt was stressed to 70% of the minimum ultimate tensile strength during installation. A superimposed bending load due to washer damage and non-uniform bearing could increase local stresses within the bolt to near or at the yield strength. Susceptibility to hydrogen embrittlement increases with increasing tensile stress. Damage to the washer prior to bolt failure could therefore promote subsequent hydrogen embrittlement fracture of the bolt.

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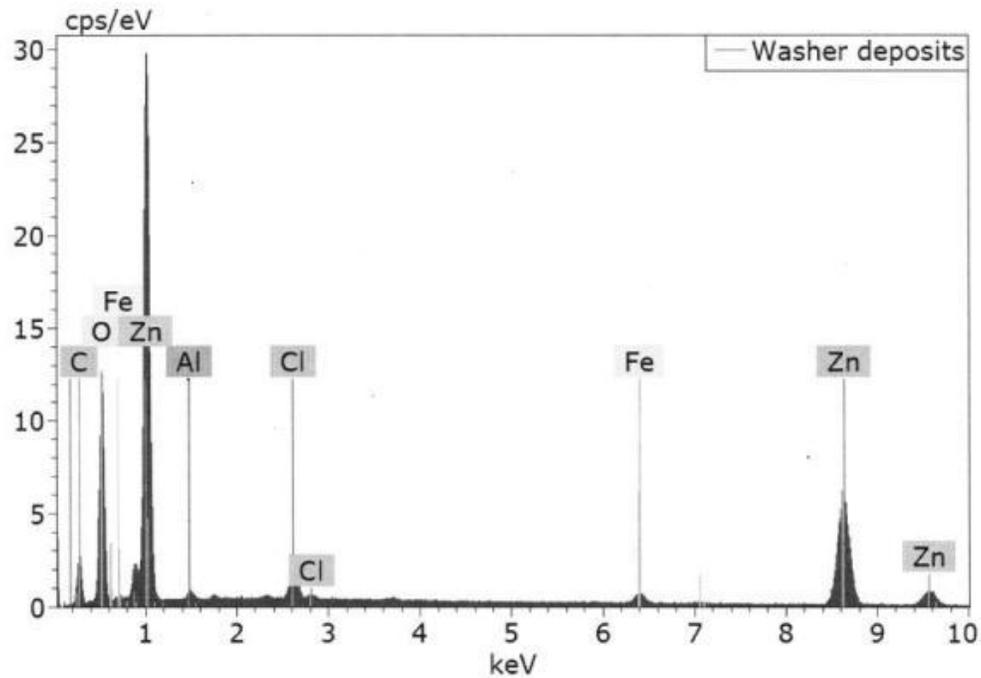


Figure 14

Energy dispersive x-ray spectra acquired from the deposited surface of the Bolt 5 washer. This sample presumably was not exposed to cutting fluids and was coated prior to our analysis, and the deposit composition should be representative of the as-fractured condition. Deposits consist primarily of zinc corrosion products. Substantial chlorine was also detected. It is not known if the chlorine exposure occurred prior to crack initiation or if exposure to chlorine was the result of fracture when the bolt dropped out of the joint and reportedly landed on the floor. Chlorine is a potent corrodant of alloy steels when present with moisture as the chloride ion, Cl^- . Corrosion of zinc coated steel can result in hydrogen generation and subsequent hydrogen embrittlement.

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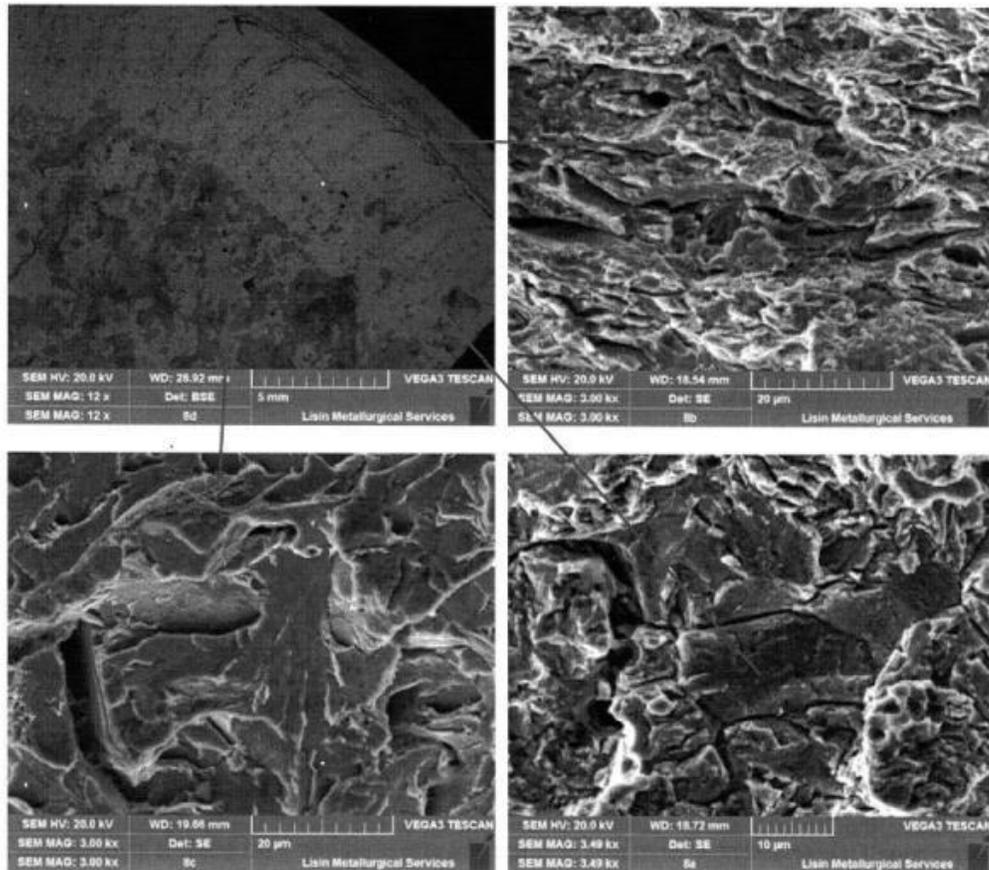


Figure 15

Backscattered electron and secondary electron images acquired from the fracture surface of Bolt 8. Fracture consisted of a mix of ductile overload and possible intergranular fracture along highly deformed grain boundaries at the thread root. A mix of ductile overload and less frequent intergranular fracture was apparent below the thread root deformation but still within the smoother crescent shaped zone of fracture initiation. The features are consistent with a mix of ductile overload and mild hydrogen embrittlement. Transgranular cleavage occurred within the large area of final overload. Cleavage fracture is consistent with high tensile stress, a limited ductility material, and a severe stress concentration at a crack tip. The fracture surface features shown above are essentially identical to those of Bolt 5, and indicate similar failure modes for the two bolts.

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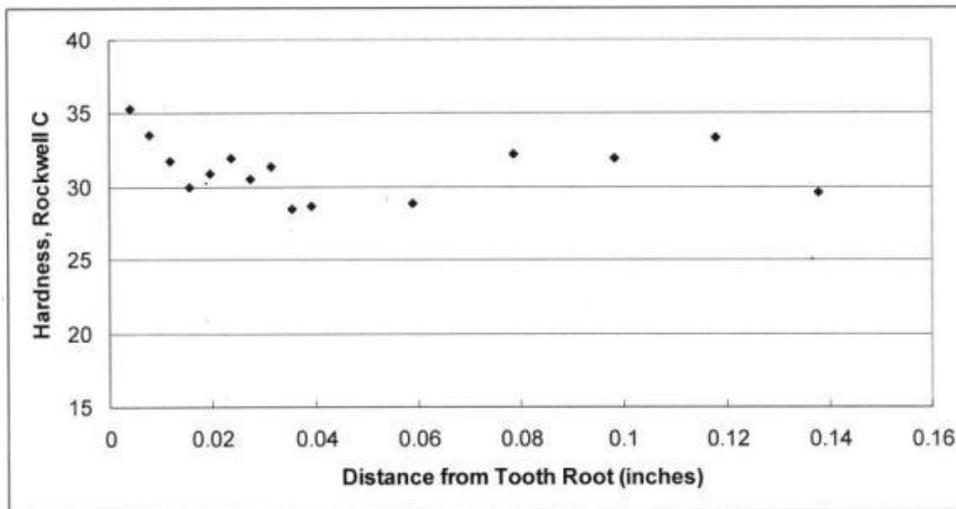
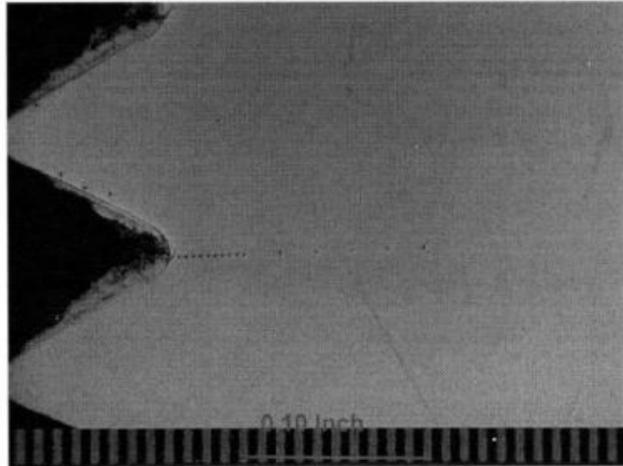


Figure 16

Bolt 5 microhardness results. Hardness values were converted from the 300 gram scale per Table 1 of ASTM E 140. For reference, a hardness of 31 to 39 Rockwell C (HRC) is specified for a 2 1/2 inch diameter or larger fastener per Grade BD of ASTM A 354. The measured core hardness is at or slightly below the specified range. The moderate increase in hardness at the thread root is consistent with work hardening due to thread rolling after completion of the harden and temper heat treatment. At mid height on the flank of the tooth from Bolt #5 the average hardness was 33 HRC.

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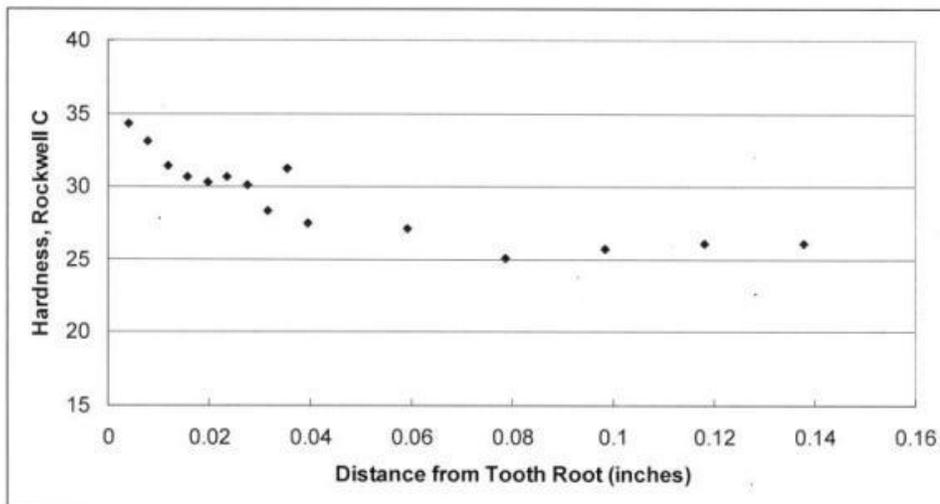
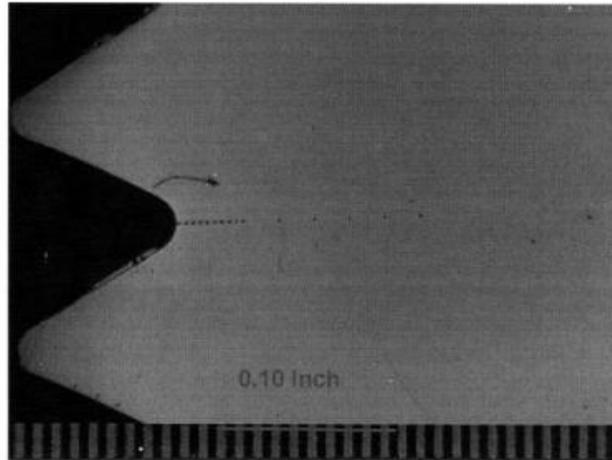


Figure 17

Bolt 8 microhardness results. Hardness values were converted from the 300 gram scale per Table 1 of ASTM E 140. For reference, a hardness of 31 to 39 Rockwell C (HRC) is specified for a 2 1/2 inch diameter or larger fastener per Grade BD of ASTM A 354. The measured core hardness is at or slightly below the specified range. The moderate increase in hardness at the thread root is consistent with work hardening due to thread rolling after completion of the harden and temper heat treatment. At mid height on the flank of the tooth from Bolt #8 the average hardness was 33 HRC.

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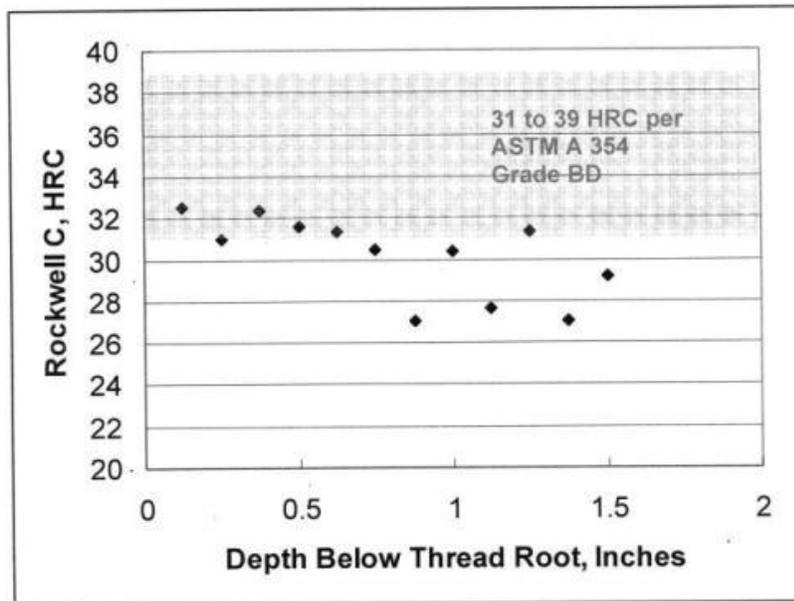
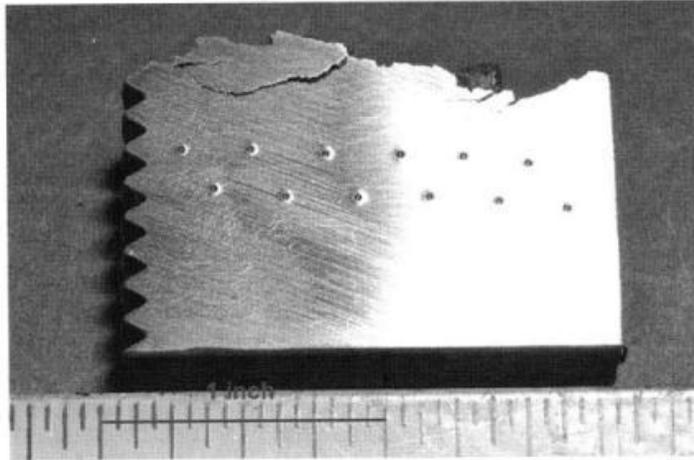


Figure 18
Direct Rockwell C hardness data obtained from a radial-longitudinal section and located three to four thread roots below the fracture. The specified hardness range for an ASTM A 354 Grade BD bolt is shown by the green band. The measured hardness at multiple locations is below the requirements of the ASTM specification.

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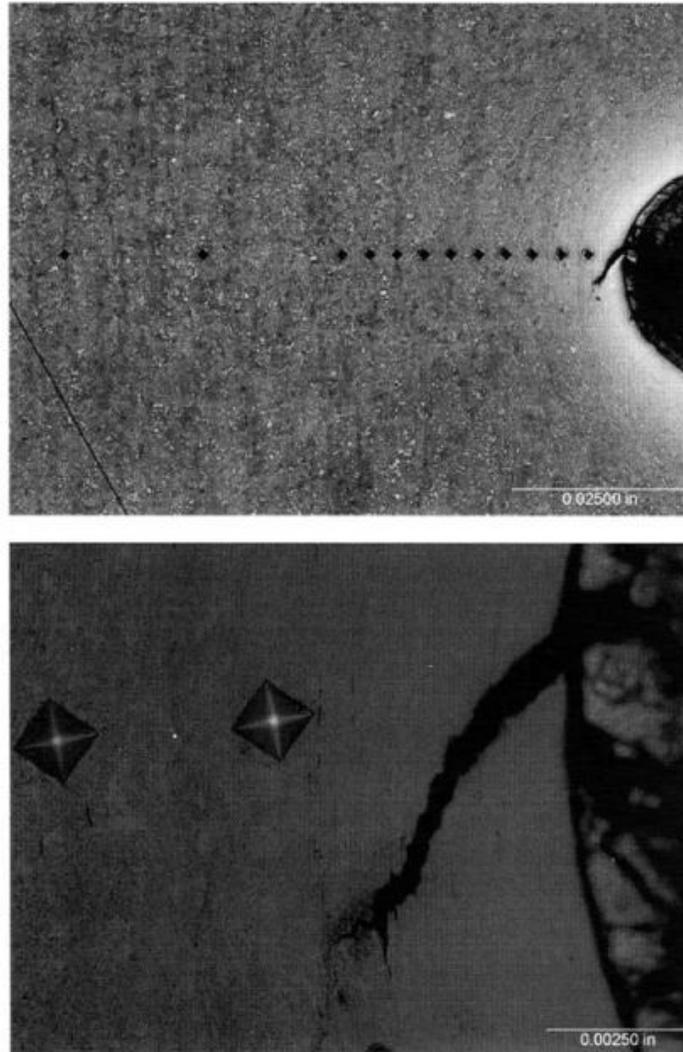


Figure 19

Longitudinal metallographic sections through the thread root adjacent to the fracture of Bolt 5. Cracking was apparent in the thread roots of the four threads adjacent to the fracture. The approximately 45° angle and wide crack is characteristic of a predominantly ductile fracture. Contour flow of inclusions along the thread root is indicative of a rolled rather than cut thread. The heavily deformed microstructure at the thread root indicates that the threads were rolled after completion of the heat treatment rather than before heat treatment. The diamond shaped features are Vickers microhardness indentations. 2% nital etch.

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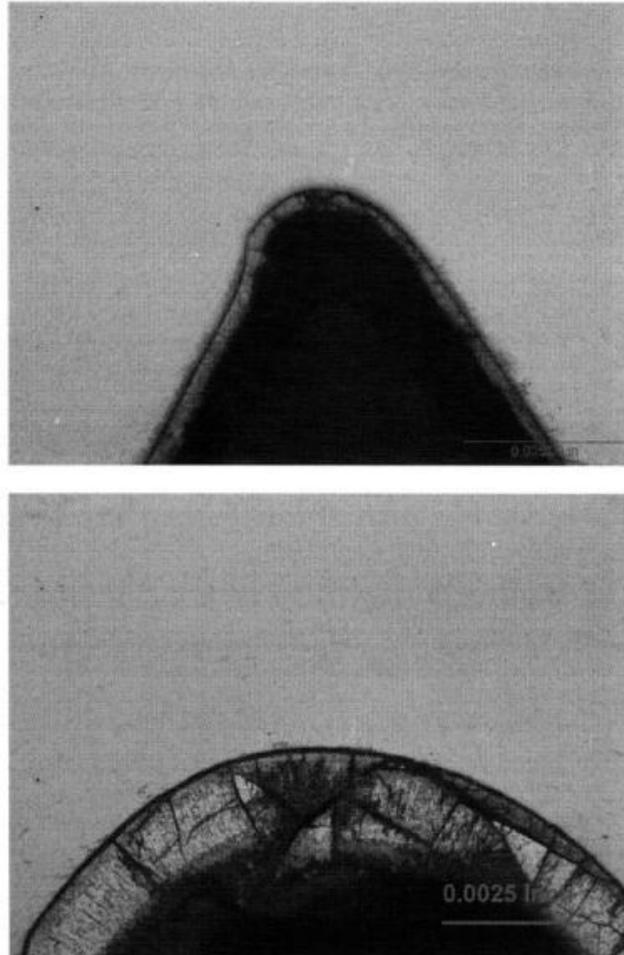
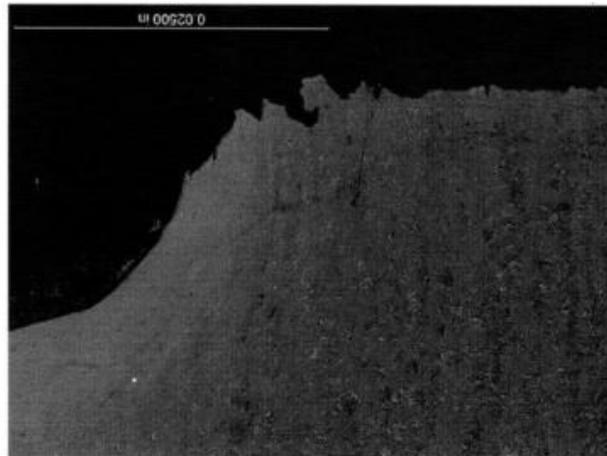


Figure 20

Longitudinal metallographic sections through the thread root adjacent to the fracture at a circumferential location roughly opposite (180°) to the apparent fracture initiation site, Bolt 5. No cracking was apparent in the four thread roots located adjacent to the fracture. Fracture initiation on one side and propagation to final failure on the opposite side suggests but does not confirm that a bending load existed in these bolts. The presence of cracks in the adjacent thread roots on the fracture initiation site and the absence of these cracks in the thread roots on the opposite side provides further evidence that a bending load existed. One likely cause of bending is the heavily deformed and cracked washers.

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Fracture Initiation



0.5 Inch below Thread Root

Figure 21

Longitudinal metallographic sections through the fracture initiation site of Bolt 5. Fracture adjacent to the thread root follows a 45° angle similar to that shown in Figure 19. The orientation of this portion of the fracture suggests crack initiation due to ductile overload. The remainder of the fracture is predominantly transverse to the axis and un-branched. Obvious intergranular fracture was not revealed by the metallographic examination. The microstructure below the thread root consisted of a mix of martensite and other transformation products, likely including fine pearlite, acicular, plate, or lath shaped ferrite, and possibly bainite. The mixed microstructure indicates incomplete transformation during hardening and is consistent with the use of a lean alloy for this large diameter. The mixed microstructure would predictably result in low hardness and low impact toughness relative to a fully tempered martensite microstructure. 2% nital etch.

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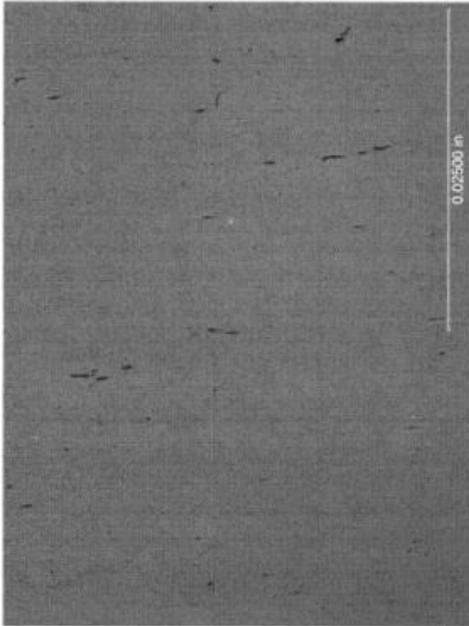
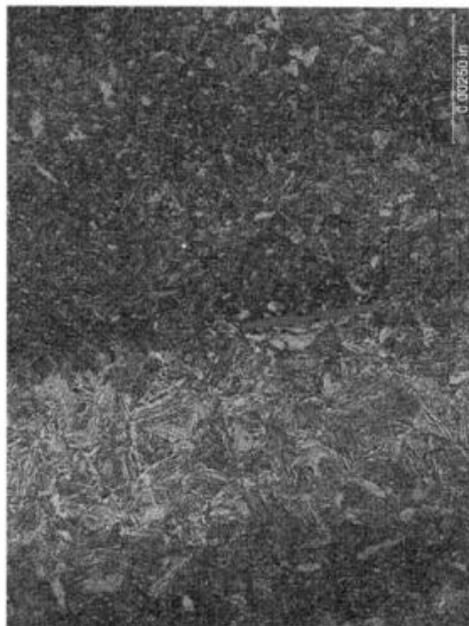
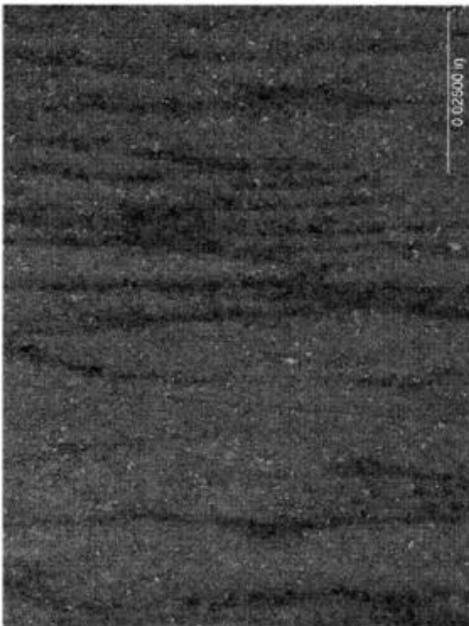


Figure 22

Longitudinal metallographic sections through Bolt 5 at a mid-radius location. The non-metallic inclusion content appeared normal for a commercial quality steel. The metallographic examination revealed a mixed microstructure of longitudinal bands of martensite and other transformation products. The microstructure is consistent with a hardened and tempered 4140 alloy steel in this diameter. A higher alloy steel such as 4340 would exhibit improved hardenability, more complete transformation to martensite, and likely better impact toughness at the same hardness level. As-polished (top) and 2% nital etch (bottom).



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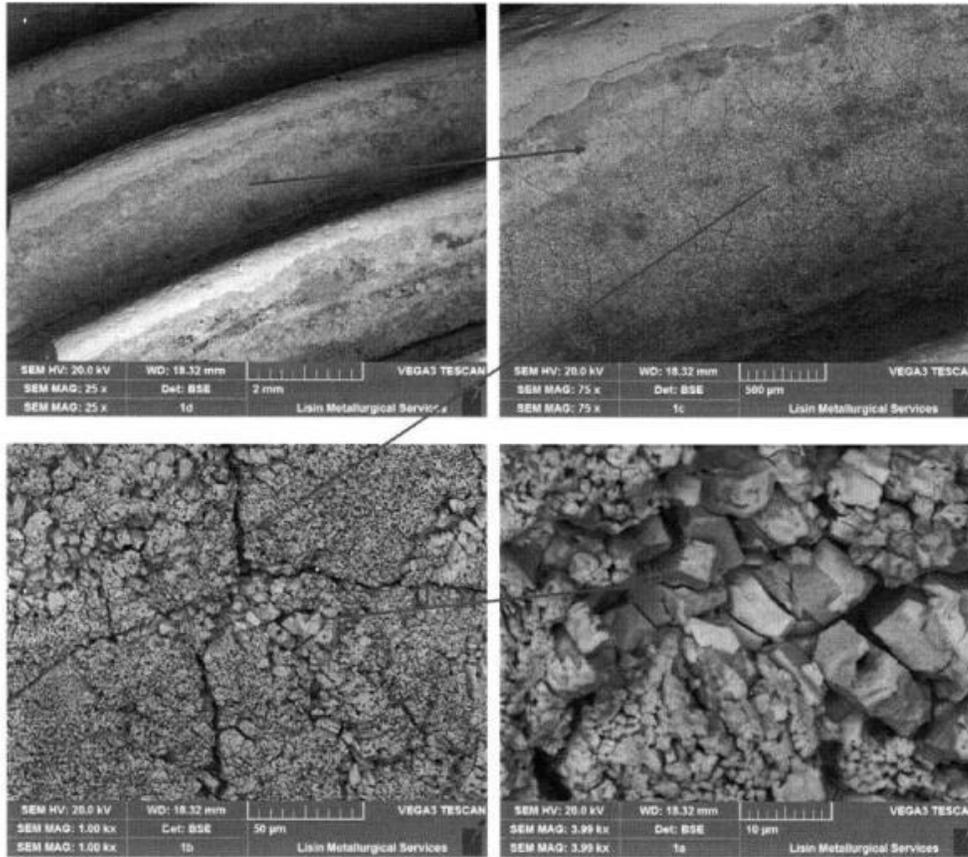


Figure 23

Backscattered electron images acquired from the threads of Bolt 5 after ultrasonic cleaning in an alkaline cleaner and an inhibited acid. The typical columnar crystal structure of a galvanized coating is readily apparent. The clear crystal structure suggests that the galvanized surface was etched due to exposure to a corrodant. Some of this corrosion may have occurred during cleaning to remove corrosion products, as both the alkaline and acid cleaning solutions are corrosive to zinc. However, substantial zinc appears to remain, indicating that the galvanized surface was not substantially degraded by mechanical damage during threading or by corrosion.

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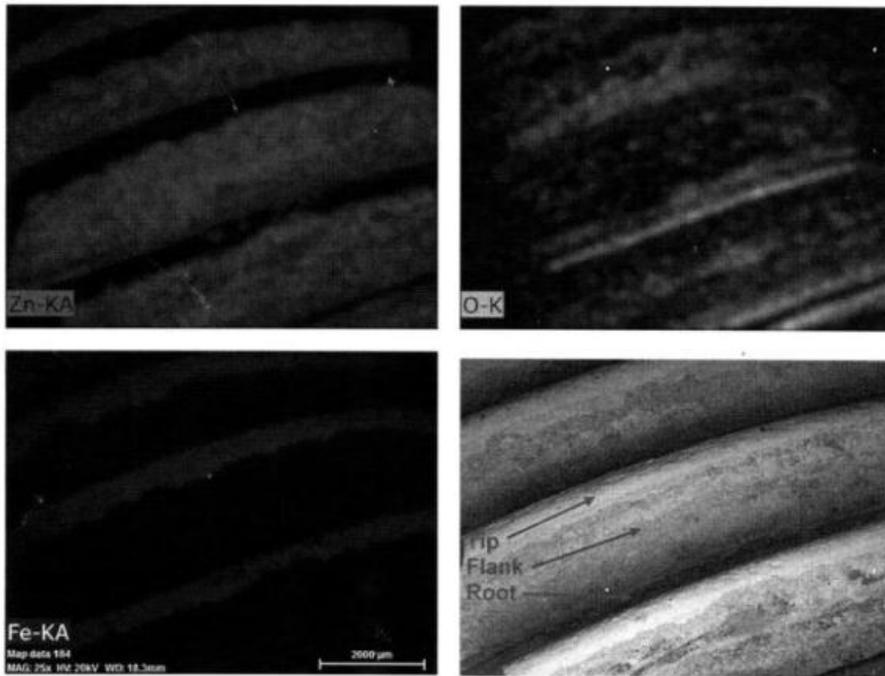


Figure 24

Backscattered electron image and x-ray maps for zinc, oxygen, and iron from threads on Bolt 5. Zinc was present on the thread flanks but not the thread tips. Iron was present at the thread tips. Oxygen appeared to be largely confined to corrosion product accumulation in the thread roots. The results suggest that the galvanized coating was removed from the thread tips, possibly due to contact with the thread roots of the nut. The zinc distribution on the thread flanks appeared to be fairly uniform, suggesting minimal mechanical damage to or corrosion of the galvanized layer on the thread flanks.

Appendix G

Lisin Metallurgical Services Failure Analysis - Report 2

DRAFT

HOOD CANAL FLOATING BRIDGE - High Strength Anchor Bolts

January 31, 2014

Bainbridge Structures Group
Attn: Robert Shulock, PE
13908 Sunrise Dr. NE
Bainbridge Island, WA 98110
E-mail: rshulock@BainbridgeStructures.com



Subject: Additional Analysis of Two Failed ASTM A 354 Grade BD 3 Inch Diameter Galvanized Steel Bolts
Lisin Metallurgical Services Job No. 524-13-002

Dear Bob,

Remnants of two fractured bolts removed from the Hood Canal Bridge (HCB) were submitted for additional Charpy impact testing, hardness measurement, and microstructural analysis. In addition, we were asked to review post fracture test results for the recent Townsend test samples ([Townsend Test Post Fracture Analysis](https://sasbridge.sharefile.com/d/s4e9dff35a524b089), December 31, 2013, <https://sasbridge.sharefile.com/d/s4e9dff35a524b089>) and test results from the fractured Bay Bridge anchor rods ([Metallurgical Analysis of Broken Bay Bridge Anchor Rods S1-G1 & S2-A6](http://www.dot.ca.gov/baybridge/a354report/H13_E2_Shear_Key_Rod_Failure_Fracture_Analysis_Report.pdf), Project #04-0120F4, May 7, 2013, http://www.dot.ca.gov/baybridge/a354report/H13_E2_Shear_Key_Rod_Failure_Fracture_Analysis_Report.pdf). The additional HCB bolt test results and results from the original HCB bolt analysis (Lisin Metallurgical Services Report No. 524-13-001) are compared to the Bay Bridge fractured bolts and the Townsend test bolts below.

Charpy Impact Energy: Charpy impact data obtained from the HCB bolt remnants at +20 and +40 °F appear in Tables 1 and 2. Charpy samples were machined from locations near the OD surface and from mid-radius locations. Note that the number of samples was limited by the small amount of available material, and complete sets of three samples per variant were not available. In fact, some variants could not be tested because of the limited amount of material available.

Charpy impact energy values from the HCB bolts ranged from 14 to 17 ft-lbs at +20 °F, and 10.5 to 18 ft-lbs at +40 °F. Consistent variation as a function of test bar location is not apparent in the data. However, the limited amount of data makes such a comparison difficult. Values at 40 °F were not significantly higher than impact energy values at 20 °F. The results suggest that the ductile to brittle transition temperature is above 40 °F for both samples and at both near surface and mid-radius locations. No acceptance criteria were provided. For comparison, one often cited criterion is a minimum impact energy of 15 ft-lbs at the lowest temperature of service. Our general understanding of the service duty suggests that these test results may not meet these criteria. The measured Charpy values from these HCB bolts are well below the 27 to 40 ft-lb values measured on the post fracture Townsend test samples but are slightly higher than the 13 to 14 ft-lb values measured on the fractured Bay Bridge anchor rods

Specializing In Failure Analysis
2335 SE Harrison, Milwaukie, Oregon 97222 Ph. (503) 657-0557 Fax (503) 657-6207 Mark@lisiinmet.com

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Hardness: Hardness data also appear in Tables 1 and 2. Hardness values were measured directly on the fractured Charpy samples, at locations away from the fracture or the anvil indentations. We would not expect work hardening in these samples at the hardness test locations due to testing, and we would not expect hardening due to the 20 °F or 40 °F test temperature. Hardness values ranged from 30 to 33 Rockwell C. The values are in fair agreement to the values measured on the actual bolts (27 to 33 HRC). For comparison, the HCB hardness values are substantially lower than the near surface hardness values on the Townsend test samples and the fractured Bay Bridge bolts, and slightly below the ASTM A 354 Grade BD requirements of 31 to 39 HRC.

Microstructure: The microstructures at both near surface and mid-radius locations of the HCB bolts consisted of a mixture of tempered martensite and other transformation products. Definitive identification of the other transformation products (bainite, pearlite, ferrite) was beyond the scope of this project. However, the cause of and result of the mixed microstructure are well documented. The alloy (4140) is a limited hardenability material and would not be expected to fully transform to martensite in this large diameter. In general, mixed microstructure steels exhibit lower fracture toughness relative to fully martensitic microstructures at the same hardness. The microstructure of each Charpy sample was evaluated. Photomicrographs of only representative samples are included in the attached figures.

The Townsend test samples were reported to exhibit microstructures of predominantly martensite. Our examination of these photomicrographs indicated a mixed martensitic / non-martensitic microstructure, but a substantially greater fraction of martensite relative to the HCB samples. This greater amount of martensite likely explains the higher Charpy impact toughness. The Bay Bridge samples exhibited a banded microstructure of martensite and non-martensitic transformation products similar in appearance to the HCB samples.

Tensile Properties: Tensile properties of the HCB bolts are compared to the Bay Bridge bolts below. The Townsend test bolts were not tensile tested.

Sample Identification	Ultimate Tensile Strength, ksi	Yield Strength, ksi	% Elongation in 4D	% Reduction of Area
HCB Bolts	153	131 to 133	17	55
Townsend Test Bolts	Not performed			
Bay Bridge Bolts	159 to 170	136 to 149	14 to 15	46 to 48
Requirements of ASTM A 354 Grade BD	140.0 Min.	115.0 Min.	14 Min.	40 Min.

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The tensile and yield strengths of the HCB bolts are slightly lower than those of the Bay bridge bolts, and the ductilities of the HCB bolts are slightly higher than that of the Bay Bridge bolts. Based on hardness and metallographic examination results, we would expect a similar trend of higher strength but lower ductility for the Townsend test bolts relative to the HCB bolts.

Alloy Chemistries: The alloy chemistries of the HCB, Bay Bridge, and Townsend test bolts are very similar and consistent with a 4140 alloy steel. Differences in the reported chemistries could be due to analytical variation among the various labs, and the various bolts could be manufactured from the same heat of steel.

Optical Fractography: Both fractured Bay Bridge anchor rods and the Townsend test bolts exhibited a "C" shaped area of progressive hydrogen related cracking followed by a larger area of final overload fracture. Fracture initiation appeared to be distributed over a broad arc of circumference (e.g. 8:00 to 4:00) and is consistent with uniform loading around the circumference due to axial loading. In contrast, the HCB bolts exhibited a similar arc shaped initiation but over a more localized area (less circumferential arc of fracture initiation). The more local fracture initiation of the HCB bolts is consistent with a combined axial tension and bending load.

SEM Fractography: Intergranular fracture was apparent within the fracture initiation sites in each of the three cases (Bay Bridge, Townsend test, and HCB bolts). Intergranular fracture is indicative of hydrogen embrittlement. Equiaxed intergranular fracture was highly pronounced in the Bay Bridge fractures but less pronounced in the Townsend test and the HCB bolt fractures. We interpret this result as evidence of varying degrees of hydrogen embrittlement. In all cases, a large area of final overload relative to the area of fracture initiation/propagation is indicative of a high stress magnitude.

Arc shaped fracture surface features were apparent near the thread roots of the Townsend test bolts and the HCB bolts. These features were not pictured in the Bay Bridge report and may or may not have existed. The arc shaped features appear to be the result of grain deformation at the surface. Deformation can result from thread rolling and thread cutting. Deformed grains extended to a depth of approximately 0.001 to 0.002 inch in the Townsend test samples, and approximately 0.04 to 0.06 inch in the HCB bolts. The results are consistent with cut threads (Townsend) and rolled threads (HCB).

Thread Manufacture: Thread manufacture (cutting vs. rolling) can be revealed by examination of a longitudinal metallographic section through the threads. Contour flow of microstructural features such as non-metallic inclusions along the thread root is generally indicative of rolled threads. Rolled threads were apparent on the HCB bolts. The report on the Townsend test bolts reported cut threads. The above is consistent with the depths of the arc shaped features on the fracture surfaces. Thread manufacture is not specifically addressed in the Bay Bridge report. However, significant surface deformation was not indicated by the SEM fractography results.

The method of thread manufacture is not trivial relative to the observed failures. Cut threads can create a different stress concentration than rolled threads. Rolled threads result in residual stresses that likely differ from cut threads. Work hardening due to thread

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rolling can result in hardness differences between cut and rolled threads in the same material. These differences occur in the more highly stressed surface material when off axis loading is present and in higher hydrogen concentrations where hydrogen is introduced at surfaces. For these reasons, differences in performance could be anticipated between the HCB bolts and the Townsend test bolts.

In summary, the failure modes and metallurgy of the Townsend test, HCB, and fractured Bay Bridge bolts are similar. Some differences in mechanical properties were revealed by the testing. One significant difference among the samples is the method of thread manufacture.

Summary tables of the additional HCB test results appear below, followed by representative microstructures exhibited by the Charpy samples. Thank you for working with Lisin Metallurgical Services on this interesting project. Please feel free to contact us with any comments or questions about these results.

Sincerely,

A handwritten signature in cursive script that reads "Mark Lisin". The signature is written in black ink on a light-colored background.

Mark A. Lisin, P.E.
Lisin Metallurgical Services

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Table 1
HCB Bolt 5 Summary of Results

Location	Charpy Values		Hardness, HRC	Microstructure
	+20 °F	+40 °F		
Surface	14.0	10.5	33, 32	Banded microstructure consisting of tempered martensite and other transformation products.
		14.0	31	
Mid-Radius	Mat'l Not Avail.	Mat'l Not Avail.	---	---

Table 2
HCB Bolt 8 Summary of Results

Location	Charpy Values		Hardness, HRC	Microstructure
	+20 °F	+40 °F		
Surface	14.0	16.0	30, 32	Banded microstructure consisting of tempered martensite and other transformation products.
	14.5	16.0	30, 31	
	15.0	18.0	31, 32	
Mid-Radius	17.0	15.0	32, 32	Banded microstructure consisting of tempered martensite and other transformation products.

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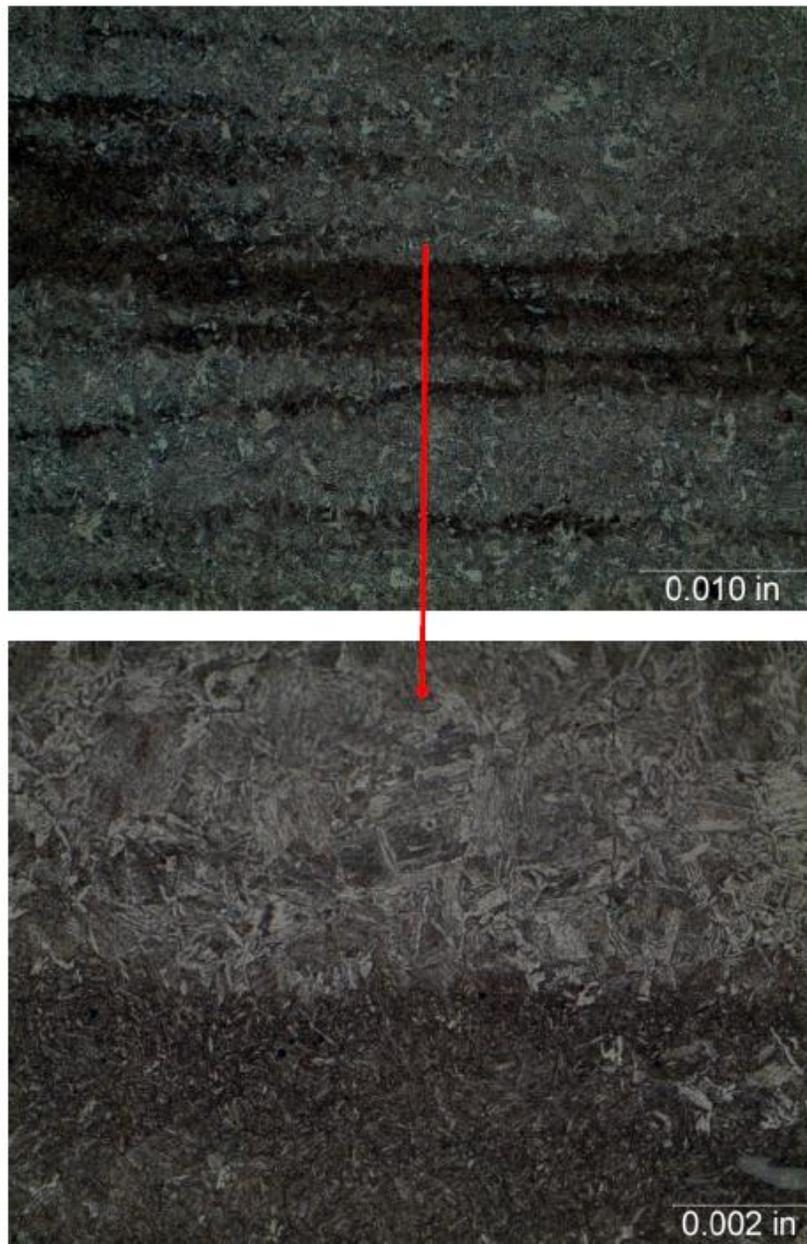


Figure 1

Longitudinal metallographic section through a Bolt 5 near surface Charpy sample. The microstructure consists of alternate longitudinal bands of martensite (darker etching) and other transformation products (ferrite, bainite, lighter etching). The microstructure is characteristic of a hardened and tempered limited hardenability alloy steel such as Grade 4140 in a thick section. The microstructure would predictably exhibit lower impact and fracture toughness relative to a fully martensitic structure at the same hardness. A higher hardenability alloy such as 4340 would likely provide a more uniform tempered martensite structure in this section thickness. The +20 °F sample is shown. Each of the three Bolt 5 surface samples exhibited a similar microstructure. 2% nital etch.

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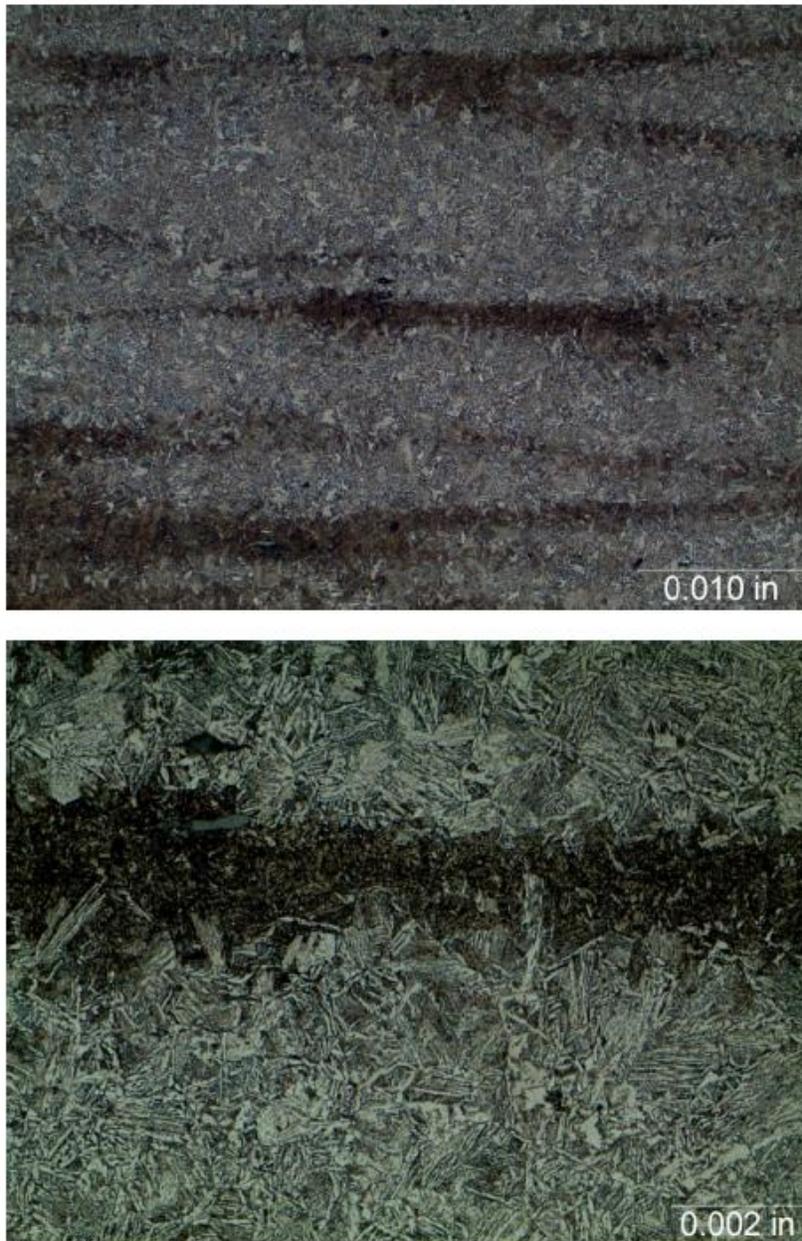


Figure 2

Longitudinal metallographic section through a Bolt 8 near surface Charpy sample. The microstructure consists of alternate longitudinal bands of martensite (darker etching) and other transformation products (ferrite, bainite, lighter etching). The microstructure is characteristic of a hardened and tempered limited hardenability alloy steel such as Grade 4140 in a thick section. The microstructure would predictably exhibit lower impact and fracture toughness relative to a fully martensitic structure at the same hardness. A higher hardenability alloy such as 4340 would likely provide a more uniform tempered martensite structure in this section thickness. The 14 ft/lb, +20 °F sample is shown. Each of the six Bolt 8 surface samples exhibited a similar microstructure. 2% nital etch.

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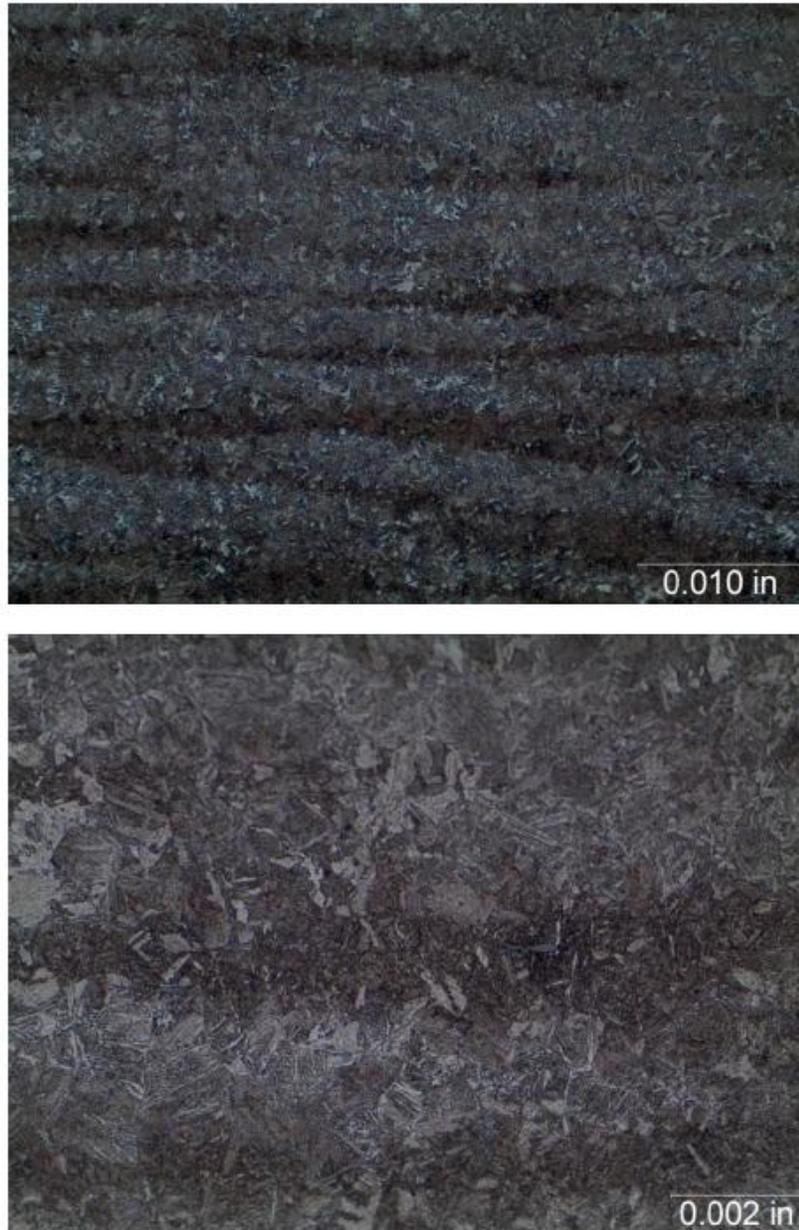


Figure 3

Longitudinal metallographic section through a Bolt 8 mid-radius Charpy sample. The microstructure consists of alternate longitudinal bands of martensite (darker etching) and other transformation products (ferrite, bainite, lighter etching). The microstructure is characteristic of a hardened and tempered limited hardenability alloy steel such as Grade 4140 in a thick section. Significant differences in the near surface and mid-radius microstructures were not revealed by the examination. The 17 ft/lb, +20 °F sample is shown. Both of the Bolt 8 surface samples exhibited a similar microstructure. 2% nital etch.

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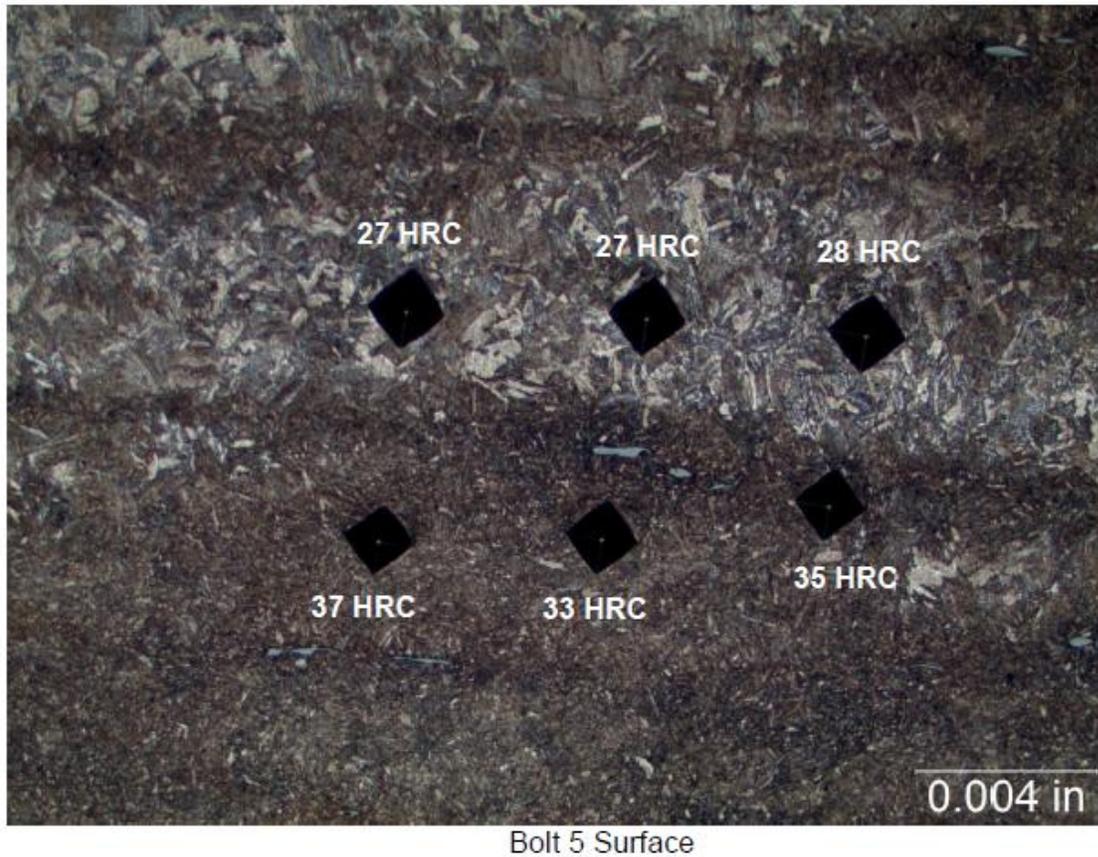


Figure 4

Vickers 300 gram microhardness indentations placed in a longitudinal metallographic section through a Bolt 5 near surface Charpy sample. The measured hardness ranged from 33 to 37 HRC within the martensitic band to 27 to 28 HRC within the lighter etching band of non-martensitic transformation products. Longitudinal banding is the result of alloy segregation during solidification. Alloy rich and alloy lean regions become elongated during rolling and result in alternating layers of high and low hardenability. Such banding is normal in commercial quality product. Non-martensitic transformation products are in general less tough than martensite at the same hardness, and the mixed microstructure likely degrades impact toughness relative to a more uniform martensitic microstructure. A higher hardenability alloy such as Grade 4340 alloy steel would likely also exhibit longitudinal banding. However, even the alloy lean areas would be more hardenable, and a more uniform martensitic structure would likely result. 2% nital etch.

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Appendix H

Jeff Gorman, Dominion Engineering Inc. - Review of the Use of Cold Rolled Threads for Anchor Rods on the San Francisco Oakland Bay Bridge (SFOBB)

DRAFT

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MEMO DRAFT



No.: M-8312-01-11, Rev. 0 draft 01

To: 8312-01 Project File

From: Jeff Gorman, Dominion Engineering, Inc.

Date: January 13, 2014

Subject: Review of the Use of Cold Rolled Threads for Anchor Rods on the San Francisco Oakland Bay Bridge (SFOBB)

1 Objective

The objective of this memo is to review the use of cold rolled threads for some of the anchor rods used on the Self Anchored Suspension (SAS) bridge section of the San Francisco Oakland Bay Bridge (SFOBB). In this regard, questions regarding the use of cold rolled threads have been raised in several reports by Y. Chung and L. K. Thomas [1], [2], and [3]. These reports reviewed information in a report by the Toll Bridge Program Oversight Committee (TBPOC), Reference [4].

2 Background

Thirty two of 96 of the first set of anchors rods installed in the SAS section of the SFOBB failed in March 2013 within about two weeks after being tensioned. This set of rods, known as the S1/S2 shear key anchor rods and identified as ID 1 on Figure 28 of the TBPOC report, had been installed in 2008 but had not been tensioned until March 2013. The long period between installation and tensioning was the result of the construction sequence of the structures that required the rods to be installed before other interfering parts were erected. During the 2008-2013 period the S1/S2 rods were in empty ducts that sometimes collected water that was periodically removed.

The S1/S2 anchor rods that failed are three inch diameter rods with cut threads made to ASTM A354 Grade BD requirements. The rods had been hot dip galvanized. The TBPOC report discusses the possible causes of the failures of the S1/S2 rods and describes the program that is underway to ensure that similar problems will not affect the other 16 sets of anchor rods that are used on the SAS section of the SFOBB.

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Of the 17 sets of anchor rods used on the SAS portion of the SFOBB, there are three sets that have rolled threads for some or all of the rods. These are (1) set 7, the parallel wire strand (PWS) anchor rods of which 229 have rolled threads and 55 have cut threads, (2) set 8, the tower top saddle tie rods, all 25 of which have rolled threads, and (3) set 16, the east cable strong back rods, all 24 of which have rolled threads. As noted in the TBPOC report, the use of rolled threads results in smoother profiles but increased hardness which could affect susceptibility to HE/SCC. The TBPOC report indicates that the effects of cold rolling on resistance to hydrogen embrittlement (HE) and stress corrosion cracking (SCC) will be explored in the planned test program.

A failure analysis was performed of two of the S1/S2 rods, as documented in Reference [5]. The main conclusions of Reference [5] were that the failures were the result of HE and could have been the result of either internal hydrogen embrittlement (IHI) or external hydrogen embrittlement/stress corrosion cracking (EHE/SCC). As noted in the TBPOC report, both possibilities are being evaluated in the test program and will be addressed in the remedial action program that is to be finalized after the test program is completed.

3 Review of Possible Risks Posed by Cold Rolled Threads

3.1 Issues Raised in Chung-Thomas Reports

The Chung-Thomas reports state that the use of threads formed by cold rolling raises risks of increased susceptibility to hydrogen embrittlement induced cracking as compared to use of cut threads. They base this conclusion on the expected high surface hardness of the material in the rolled area, which is expected to decrease the threshold stress intensity factor (K_{Isc}) of the hardened material to a low level. To address this situation, the Chung-Thomas reports state that:

1. A K_{Isc} -hardness curve based on tests of material from new 2013 anchor rods should not be used since it would not reflect the effects of rolling. Rather, a separate K_{Isc} -hardness curve needs to be developed for the rolled rods using 20 full size anchor rods as test specimens. In this regard, use of small size test specimens as planned per Test V (Raymond tests) is not acceptable since it will not properly account for the effects of the local surface hardening induced by cold rolling.
2. For cases where dehumidification is used as a remedial measure, the spaces need to be air tight, the relative humidity needs to be controlled to a specified value, and the relative humidity needs to be monitored

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3.2 Discussion

3.2.1 Effect of Rolled Threads on Fatigue and SCC

An initial search has been made of the technical literature to determine where rolled threads are used and if there are any reports of the use of rolled threads having caused, or been associated with, HE/SCC. This included a review of standard handbooks that address design and application of bolting, as well as other technical documents (References [7, 8, 9, 10, 11, 12]). This review indicates that rolled threads have been widely and successfully used for bolting in high stress, high fatigue applications, e.g., for military aircraft landing gear. This is a result of the superior fatigue performance of the rolled threads and is attributed to the high compressive stresses developed at the root of the thread by the rolling process, and the smoother surface produced by rolling as opposed to machine cutting. No reports of problems caused by use of rolled threads were found, with one possible exception, as discussed later.

The factors that make rolled threads perform better in high fatigue duty applications, i.e., high residual compressive stresses and smooth surfaces, also increase resistance to stress corrosion cracking (SCC), as indicated by the tests documented in References [12, 13, 14]. It is expected that this also applies to SCC associated with hydrogen embrittlement (HE). This is because it is the presence of high tensile stresses at the roots of threads that is believed to result in the accumulation of hydrogen in that region and to lead to decohesion and cracking. The compressive stresses induced by rolling are expected to strongly decrease this tendency.

BAMC found that anchor rods with sizes and loads similar to those on the SAS have been used successfully for many years in the Hood River Floating Bridge (HCFB) [15]. Many of the highly loaded anchor rods in the newer replacement East section of the HCFB are known to have rolled threads, and have performed satisfactorily for over four years [15] (whether the similarly loaded rods in the older West half of the bridge, which has operated satisfactorily for over 30 years, have rolled threads is not known). As noted in Reference [15], some of the three inch diameter rods with rolled threads failed in 2009 in the shipyard within one to two weeks after being tensioned, before the new East section of the bridge was put into service. These failures were determined to be caused by hydrogen embrittlement as the result of high bending stresses and strains caused by the use of undersized washers. Operation of the rods with rolled threads has been without failures once this initial design problem was corrected by use of appropriately sized washers.

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As noted earlier, there are many reports regarding the use of rolled threads to improve fatigue lives and resistance to SCC in many material-environment systems. A review of the technical literature found only one report of SCC occurring in bolts with rolled threads. This case involved peened and rolled precipitation hardened austenitic stainless steel Alloy A-286 bolts that experienced SCC during an in-reactor test with applied general shank stresses of 108% of the yield strength [16]. It was concluded that applying stresses above the proportional limit of the material could lead to development of tensile stresses in the cold worked layer and lead to SCC.

The tests to be performed per Test IV of full size anchor rods and per Test V of samples with rolled threads are expected to determine whether the rolling reduces the resistance of the rods to HE and SCC. Both types of tests will subject the rolled threads to high applied stresses in a sodium chloride solution to determine the stress at which HE/SCC occurs. The results of these tests are expected to provide a firm basis for determining the acceptability of the anchor rods with rolled threads.

The Chung-Thomas reports state that a new K_{Isc} – hardness curve needs to be developed for the rolled threads. In this regard, the rolled areas are expected to have high hardness and therefore low K_{Isc} values. This is also the case for the many material-environment systems where rolled threads have been used, but has not caused problems. This is attributed to the high compressive residual stresses in the rolled area, which keeps the applied K_I at values below the material's K_{Isc} , such that no crack growth occurs. It is considered that tests to measure the low K_{Isc} of the hardened material at the root of the thread are unnecessary since it is clear that K_{Isc} will be low and since, more importantly, the low K_{Isc} of the rolled material does not lead to occurrence of SCC because of the high compressive residual stresses in the rolled area.

3.2.2 Concerns Based on Effects of Hydrogen Sulfide

In Reference [3], the Chung-Thomas report notes that cracking of steels in hydrogen sulfide environments is aggressive and is attributed to HE, i.e., to the same mode of cracking that could possibly affect anchor rods on the SAS. They further note that NACE requires cold rolled threads used in hydrogen sulfide environments to meet the hardness limits of the bolt specification. This indicates that, for hydrogen sulfide service, cold rolled threads might need to be heat treated after rolling to reduce the high surface hardness induced by rolling. This requirement seems to be in contradiction to the published literature cited previously which indicates that cold rolling increases resistance to both fatigue and SCC. Nevertheless, to more fully explore this situation, and to ensure that HE is not aggravated by use of cold rolled threads, a literature search on this subject has been initiated. Completion of this search is not expected until about January 20. However, the abstract of one relevant document has already been

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located, Reference [17]. The abstract of this paper indicates that cold rolled threads increased the fatigue endurance limit of steel bolts in a hydrogen sulfide contaminated salt water environment by over a factor of two as compared to cut threads, which indicates that resistance to HE was not reduced by use of cold rolling, even in an aggressive hydrogen sulfide environment. The full document will be obtained and reviewed, together with any other relevant documents identified in the on-going literature search.

3.2.3 Effects of Hot Dip Galvanizing on Cold Rod Threads

Chung-Thomas note in Reference [3] that the high temperatures involved in hot dip galvanizing, which is typically performed at about 850°F, are expected to reduce the compressive stresses induced by cold rolling and that this could adversely affect resistance to HE/SCC. Reference [3] further notes that there seems to be no published literature regarding the SCC/HE performance of steels with cold rolled threads that were hot tip galvanized, and recommends that tests be performed to investigate this concern.

The literature searches performed thus far have not located any published literature that discusses tests or service experience with hot dip galvanized cold rolled threads. However, as discussed in Reference [15], anchor rods of similar sizes and loads in the east half of the Hood Canal Floating Bridge (HCFB) have cold rolled threads and have operated for over four years without problems. (There were failures of the rods in the shipyard before the new section was put into service due high bending stresses at the bottom of the rod caused by use of too thin a washer. However, this was corrected before the new section of the bridge was put into service.) The service environment for the HCFB rods is quite severe in terms of both wetting by seawater and by high loads during storms. It should be noted that good corrosion protection measures have been applied, such as use of grease in areas where rods are embedded in concrete, and use of a three coat paint system for areas exposed to the weather. The experience at the HCFB indicates that hot dip galvanized rods with cold rolled threads are resistant to HE/SCC as long as they are adequately protected against corrosion.

3.2.4 Dehumidification

The PWS anchor rods and several other sets of anchor rods are installed in spaces that are already or soon will be dehumidified. It is understood that these spaces are sealed by air tight doors, that the relative humidity in these spaces is controlled to about 40%, and that the relative humidity is continuously monitored.

4 Preliminary Conclusions Related to Rolled Threads

Based on information gathered to date it is preliminarily concluded that rolled threads are expected to increase, rather than decrease, the resistance to HE/SCC of the anchor rods on the SAS. While the hardened material at

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the root of the thread will have a low K_{Isc} , this is not important since the high compressive residual stresses at the root of the threads prevent crack initiation or propagation in this area. It is considered that there is no need to measure the K_{Isc} of the hardened material at the root of the thread since it can be estimated based on its hardness. In addition, an accurate value of K_{Isc} is not needed since the compressive stresses in the rolled areas prevent crack initiation and growth.

The above conclusions are considered to be preliminary since an additional search of the literature is underway to better understand the behavior of rolled threads in hydrogen sulfide environments.

The dehumidification systems installed on the SAS meet the requirements suggested in the Chung-Thomas reports and are expected to minimize risks of HE/SCC of the anchor rods installed in the dehumidified spaces.

5 References

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Appendix I

Summary History – Placement of A354 Anchor Bolts

DRAFT

Date	Activity	Comment	Reference
6/9/2005	(3" and 4") A354 bolts shipped from Dyson to Thompson Metal Fab,	Bolts shipped galvanized and with rolled threads	Ref MTRs
7/16/2007	Finish - Float-out and delivery to Todd Shipyards of all Draw Span pontoons	Assembly and outfitting of draw spans accomplished at Todd Shipyards in Seattle, WA	REF HCB Post-Construction Report
6/1/2007	Start - Draw Span assembly		REF HCB Post-Construction Report
10/10/2007	Start - Draw Span outfitting		REF HCB Post-Construction Report
2/26/2008	A354 bolts shipped from Thompson Metal Fab to Kiewit - General		Ref COCs
6/1/2008	Lift Span delivered to Todd Shipyards		Ref HCB Monthly Report JUN08
8/13/2008	Lift Span and bolts installed w/ one bolt w/o top nut	Bolts were installed prior to erection of lift span. No cover is seen on bolts and one bolt shown has no nut at the top.	Ref construction photos
10/22/2008	Thread failure when tightening 4in bolt (7th - 4in bolt tightened)	Two new 4in bolts ordered from Dyson	Ref WSDOT emails correspondence.
2/2/2009	WSDOT orders new ungalvanized nuts.		Ref WSDOT Material Order Approval
3/12/2009	Begin - Bolt tensioning	Assumed beginning to allow testing of draw span. Most of new washer/nuts received by March 11, 2009.	Ref MTR's
3/13/2009	Lift and Draw Span Tests	20 consecutive draw span open/close operations were successfully performed.	Ref HCB Monthly Report MAR09
3/30/2009	Draw Span conditional acceptance		REF HCB Post-Construction Report
4/17/2009	Finish - Bolt Tensioning	Anecdotal finish as reported by WSDOT engineer was 1 to 2wks prior to fracture. Last of nuts rec'd April 7, 2009	Ref WSDOT email correspondence & MTR's
4/24/2009	3 in Bolt 5W - Found fractured 3 in Bolt 8W - Fractured 2 hrs later 3 in Bolt 8E - Fractured after 8W	One bolt found fractured date uncertain, two bolts fracture Apr 24. Photos indicate that bolts were not greased nor painted.	Ref WSDOT construction documents, email correspondence & site photos.
4/30/2009	Three more 3 in bolts fracture Other six - 3 in bolts determined failed by plastic deformation	Photos indicate that bolts were not greased nor painted.	Ref WSDOT construction documents, email correspondence & site photos.
5/18/2009	Draw span float-in		Ref Newspaper Article
6/3/2009	Bridge Opened for traffic		Ref HCB Monthly Report May-JUN09