San Francisco-Oakland Bay Bridge Seismic Safety Project

FHWA Review of the A 354 Grade BD Bolts Used in the Self-Anchored Suspension Bridge

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EXECUTIVE SUMMARY

In response to the Toll Bridge Program Oversight Committee's request for FHWA to conduct an independent review of their strategies for resolution of the galvanized A354 Grade BD Bolts used in the new Self-Anchored Suspension Bridge, FHWA formed a review team. There are a total of 2306 bolts/rods in 17 locations on the new bridge.

The FHWA Review Team (the Team) conducted an extensive review of the information provided on the bolts and the retrofit of Shear Keys S1 and S2 at Pier E2. In addition, the Team supplemented the review with field visits, technical meetings, teleconferences and interviews of experts familiar with the bridge. The Team was impressed with the project team's documentation on in-depth design and analysis, and the expertise engaged by Caltrans in assisting with the design, construction and related issues. Equally impressive was the TBPOC's investigative process to help develop the strategies for the disposition of the A354 Grade BD bolts/rods used in the SAS, and more specifically the rods used in the bearings and shear keys in Pier E2.

The Team concurs with the following actions taken or planned by TBPOC *[See Reference No. 36]*:

1. Abandoning all the anchor bolts in Shear Keys S1 and S2, and retrofit with a steel strand post-tensioning system to replace their clamping force.
2. Continuing to perform the Townsend and Raymond Tests in support of preparing inspection, monitoring, maintenance, repair and replacement plans for the remaining A354 Grade BD bolts used in 17 locations of the SAS. This work can take place while traffic is moved to the new bridge.
3. Engaging national and international experts to assist in dealing with the current issues of the A354 Grade BD bolts.
4. Determining and establishing the near-term and long-term management of the bolts.
5. Assessing protection measures, such as, dehumidification, shielding, lowering tension forces, to minimize the potential for stress corrosion cracking.
6. Preparing "Bridge Maintenance and Inspection Manuals" for each of the major components of SAS, including the existing A354 Grade BD bolts.

In addition, the Team developed two documents as shown in Appendices A and B to assist TBPOC and Caltrans prepare the special provisions for ordering new replacement bolts and in prioritizing the inspection, monitoring, maintenance and replacement of the A354 Grade BD bolts/rods.

San Francisco-Oakland Bay Bridge Seismic Safety Project

Report by the FHWA Review Team on Strategies for Inspection, Maintenance, Repair and Replacement of the A 354 Grade BD Bolts used in the Self-Anchored Suspension Bridge

PURPOSE

The purpose of this report is to document the findings and recommendations of the FHWA Review Team (the Team) on the review of the Toll Bridge Program Oversight Committee's (TBPOC) strategies for resolution of the A354 Grade BD bolts used on Pier E2 and other locations of the new Self-Anchored Suspension Bridge.

BACKGROUND

The California State Legislature tasked TBPOC to oversee the new east span project. TBPOC is comprised of the Director of the California Department of Transportation (Caltrans), the Executive Director of the Bay Area Toll Authority (BATA), and the Executive Director of the California Transportation Commission (CTC).

In early March 2013, TBPOC discovered 32 galvanized A354 BD bolts that were embedded in Shear Keys S1 and S2 in Pier E2 had failed a few days after tensioning. After a methodical and thorough investigation, TBPOC concluded that the bolts failed due to hydrogen embrittlement (HE), with source of hydrogen being both internal and external. TBPOC designed a retrofit solution to replace all of the bolts that were manufactured in 2008 and embedded in Shear Keys S1 and S2 in Pier E2. In addition, there are numerous similar galvanized A354 BD bolts in Pier E2 and at other locations on the new bridge. The locations and uses of these bolts are shown in the attachment to Reference No. 1. TBPOC has been reviewing, testing, and evaluating to determine if any further remedial action is required. Based on their findings and recommendations, TBPOC has classified the bolts into the following categories for the purpose of rod-by-rod resolution *[See Reference No. 36]*:

1. Rods whose clamping capacity is to be replaced before opening the bridge to traffic;
2. Rods that are to be replaced after opening the bridge, as a precautionary measure to address concerns of longer-term stress corrosion;
3. Rods that are subject to mitigating actions, such as reduced tension, dehumidification or other corrosion protection systems; and
4. Rods that are acceptable for use, will meet performance expectations, and will undergo a regular inspection schedule.

(It may be noted that bolts, rods and fasteners are used interchangeably in this report and in the TBPOC's reports.)

Bolts/rods in Category 1 were identified and a decision was made to abandon them and replace the clamping capacity with a post-tensioning system. Resolution on bolts in Categories 2, 3 and 4 are pending completion of the Townsend and Raymond Tests *[See Reference No. 36]*.

REQUEST FROM TBPOC TO FHWA

On May 8, 2013, TBPOC sent a letter *[See Reference No. 1]* to Mr. Vince Mammano, FHWA California Division Administrator, requesting FHWA to conduct an independent review of their strategies for resolution of the A354 Grade BD bolts used on Pier 2 and other locations of the new bridge under the following categories:

1. Bolts to be replaced before opening the bridge to traffic,
2. Bolts to be replaced after opening the bridge, as a precautionary measure to avoid premature failure due to stress corrosion, and
3. Bolts to undergo a regular inspection schedule and be replaced as necessary if damage is observed in routine use.
    - TBPOC also is looking at protection measures such as dehumidification, shielding, and lower tension values.

In response to the TBPOC's request, FHWA immediately formed a Review Team to:

1. Conduct field visits of the bridge;
2. Meet with TBPOC, Caltrans and Consultants to gain a better understanding of the issues and solutions; review contract documents and as-built information and drawings;
3. Review TBPOC and Caltrans investigations, findings and recommendations;
4. Interview personnel in design, construction, inspection and testing to gain a better understanding of the issues from the expert's point of view;
5. Report on findings and recommendations.

The FHWA Review Team appreciated the opportunity to conduct review of the strategies for managing the disposition of the A 354 Grade BD bolts in the Self-Anchored Suspension Bridge (SAS) in the near- and long-term.

FHWA REVIEW TEAM MEMBERS

1. Myint Lwin, PE, SE, Director, Office of Bridge Technology, HQ (Lead)
2. Joey Hartmann, PhD, PE, Team Leader, Bridges and Tunnels, Office of Bridge Technology, HQ
3. Waider Wong, PE, Senior Structural Engineer, Resource Center in Baltimore, MD
4. Justin Ocel, PhD, PE, Research Structural Engineer, Office of Infrastructure Research and Development, FHWA Highway Research Center
5. Greg Kolle, P.E., Senior Structural Engineer, California Division Office, Sacramento, CA
6. Brian Kozy, PhD, PE, Senior Structural Engineer, Steel Specialist, Office of Bridge Technology, HQ
7. Reggie Holt, PE, Senior Structural Engineer, Concrete Specialist, Office of Bridge Technology, HQ

ACTIVITIES OF THE FHWA REVIEW TEAM

1. Conducted two trips to review field conditions of the locations where ASTM A354 Grade BD bolts/rods were used, with special attention to the bearings and shear keys in Pier E2.
2. Met with TBPOC, Caltrans, Consultants and others through face-to-face meetings and teleconferences. They held extensive technical discussions to ensure that the plans for inspection and testing of the bolts were developed comprehensively in support of sound decisions for the disposition of the bolts/rods, the study of alternative retrofit schemes, and the final selection of the most effective retrofit for construction.
3. Reviewed 18 volumes of general and technical information on the 17 locations where A354 Grade BD bolts are used in the Self-Anchored Suspension Bridge (SAS). These 18 volumes documented the "Notice to Contractors and Special Provisions" for the SAS contract. *[See References 10 through 27]*
4. Reviewed the following Caltrans' reports on their investigations, testing, findings and recommendations:
    a. Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge with Findings and Decisions (Bolt Reports) dated July 8, 2013 *[See Reference No. 36]*. This report provides a detailed description of the TBPOC actions and decisions relating to the investigative process, and the decision factors used in replacing the failed 2008 A354 Grade BD bolts with a post-tensioning system. A rendering of the system is shown in this report.
    b. Report on "SAS A354BD Testing Program Results on Test I, II & III" (Test Report) dated June 12, 2013 *[See Reference No. 35]*. The Testing Program consists of five tests, namely, (1) Test I Field Hardness Test, (2) Test II Laboratory Test on Samples, (3) Test III Full-Size Test, (IV) Stress Corrosion Test (Also called the Townsend Test), and (5) Test V Incremental Step Loading Test (Also known as the Raymond Test).

Tests I, II and III have been completed with results showing hardness, Charpy values and chemistry of the bolts. Tests IV and V are in progress. These tests will determine the susceptibility of the bolts to hydrogen embrittlement and stress corrosion cracking.

LIST OF EXPERTS ENGAGED BY CALTRANS/BATA *[See Reference No. 29]*

Experts engaged by the California Department of Transportation (Caltrans):

Herbert Townsend Jr. Ph.D., P.E., Senior Fellow at Bethlehem Steel, Townsend Corrosion Consultants Inc. Expertise: Corrosion performance and testing of coated and low-alloy steels for the automotive and construction industries.

Karl H. Frank, Ph.D., P.E., Professor Emeritus, University of Texas at Austin, Department of Civil, Architectural and Environmental Engineering, Hirschfeld Industries, Chief Engineer. Expertise: Design and behavior of structural steel bridges, fracture and fatigue behavior of metal structures.

Sheldon W. Dean Jr., Sc.D., Air Products and Chemicals, Inc., Chief Engineer - Materials, Dean Corrosion Technology Inc, President. Expertise: Corrosion Engineering.

Bob Heidersbach, Ph.D., P.E., Professor, Oklahoma State, Chemical Engineering, Metallurgist at the U.S. Army Construction Engineering Research Laboratory, Professor & Chair, California Polytechnic State University, Materials Engineering Department, Dr. Rust Inc., President. Expertise: Metallurgy and corrosion, failure analysis oil and gas industry, military hardware, construction

Alan W. Pense, Ph.D., Professor Emeritus, Lehigh University, Department of Materials Science and Engineering, former Provost, Associate Director of the Center for Advanced Technology for Large Structural Systems at Lehigh for 3 years. Expertise: Metallurgy, welding, joining and failure analysis of large structures

Charles J. McMahon, Jr. Sc.D., Professor emeritus, University of Pennsylvania, Department of Materials Science and Engineering. Expertise: Mechanical Behavior, Metals, Surfaces & Interfaces, diffusion-controlled crack-growth

Louis Raymond, Ph.D., P.E.
Aerospace Corporation (research on the Titan Launch Vehicle), Worked on Failure analysis of the Shuttle Challenger, Lou Raymond and Associates, President (current), Fracture Diagnostics International (current), Adjunct Professor, California State University Long Beach. Expertise: Failure analysis, Fracture Mechanics, Coated Alloy Steel fasteners, Hydrogen Embrittlement testing, Corrosion.

Expert engaged by the Bay Area Toll Authority (BATA):

Jeffrey A. Gorman, Ph.D., P.E., Expertise: Materials, failure analysis, corrosion and water chemistry.

Others:

Dr. John Fisher, Ph.D., member of the Toll Bridge Seismic Safety Peer Review Team
Dr. Frieder Seible, Ph.D., member of the Toll Bridge Seismic Safety Peer Review Team

FHWA RECOMMENDATIONS

The FHWA Review Team recommends the following for consideration in setting priorities in inspection, monitoring, maintenance, protection measures, and replacement of bolts:

1. Perform Ultrasonic Testing (UT) of the threaded parts of the A354 BD bolts in the bearings and shear keys in Pier E2 to establish baseline conditions for future inspection and evaluation of the condition of the bolts.
2. Use the Greg Assessment Tool *[See Appendix B]* developed by FHWA for determining the vulnerability of the bolts to hydrogen embrittlement or stress corrosion cracking.
3. Use plastic ducts and couplers in the post-tensioning system for the retrofit of Shear Keys S1 and S2. Plastic ducts and couplers meet the intent of the Post-Tensioning Institute's Protection Level 2 (PL2)
4. Identify and implement protection measures, such as, dehumidification, shielding, lowering tension forces, enhanced inspection intervals and techniques, as effective strategies for

managing the existing bolts. Once a protection measure has been established, it should be implemented as soon as practicable.

5. Inspect chambers with dehumidification systems to make sure they are operational as early as feasible.
6. When ordering new bolts for replacement, consider the following in the Special Provisions *[See Appendix A]:*
   a. Limit the tensile strength and hardness.
   b. Require minimum toughness (CVN).
   c. Supplement ASTM Specifications with Special Provisions for QC/QA testing to avoid misunderstanding or misinterpretation.
   d. Assure that the testing required by the ASTM Specifications and Special Provisions is conducted.
7. Inspect welded or bolted components for details where water and debris may collect. Retrofit to allow water to drain and debris to be removed.
8. Consider changing the cast-in-place concrete blister at the base of the anchor rods at Pier E2 to a system that allows access for inspection, testing and replacement of the anchor rods.

CONCLUSION

The Team appreciates the opportunity and is impressed with the dedication, commitment, and the high calibers of the engineers in working on this effort. They put in long hours to provide us with reports and answers, meeting with us for detailed discussions of the contents of the reports, and accompanying us in the field visits.

The Team concurs with the following actions taken or planned by TBPOC *[See Reference No. 36]*:

1. Abandoning all the anchor bolts in Shear Keys S1 and S2, and replace their clamping force with a steel strand post-tensioning system.
2. Continuing to perform the Townsend and Raymond Tests in support of preparing inspection, monitoring, maintenance, repair and replacement plans for the remaining A354 Grade BD bolts used in 17 locations of the SAS.
3. Engaging national and international experts to assist in dealing with the current issues of the A354 Grade BD bolts.
4. Determining and establishing the near-term and long-term management of the bolts.
5. Assessing protection measures, such as, dehumidification, shielding, lowering tension forces, to minimize the potential for stress corrosion cracking.
6. Preparing "Bridge Maintenance and Inspection Manuals" for each of the major components of SAS, including the existing A354 Grade BD bolts/rods.

The Team has sufficient information and data to support TBPOC's near-term decisions to retrofit Shear Keys S1 and S2 with a post-tensioning system to restore the clamping force lost by the failed/abandoned anchor bolts. The Team has reviewed the retrofit system and concurs with the approach as a solution to replace the failed bolts.

The disposition of the remaining A354 Grade BD bolts/rods will depend on the Townsend and Raymond Tests being conducted. These tests are more time consuming and may not have results until after the bridge is opened to traffic. The data from these tests and the FHWA Greg Assessment

Tool will assist TBPOC in setting priorities for inspection, maintenance, protection measures and replacement of bolts.

The Review Team will be happy to help with setting priorities for the inspection, monitoring, maintenance and replacement of the existing bolts. The Team is also happy to review the bridge inspection and maintenance manuals in the future, if desired by TBPOC.

REFERENCES

DOCUMENTS RECEIVED FROM TBPOC/CALTRANS FOR REVIEW:

Reference Number	Date Rec'd (2013)	Document Description
1	5/8	May 8, 2013 letter from Toll Bridge Program Oversight Committee to Mr. Vincent Mammano, California Division Administrator, FHWA
2	5/14	A354 Gr BD Rods installation status data sheet
3	5/14	Metallurgical study on A354 Gr BD rods
4	5/16	ASTM Specifications (A123/A 123M-01a, F606-11a, A354-11, A143/A 143M)
5	5/22	Change order letters (from mechanical galvanizing to hot-dip galvanizing)
6	5/22	SFOBB SAS A354 Gr BD location draft information (Tables & Pictures)
7	5/23	Bolt tensioner information
8	6/3	SAS Pier 2 Shear key anchorage retrofit design baseline plan
9	6/3	Caltrans 5 /29/13 briefing on BB bolts to the press (powerpoint)
10	6/4	QA Auditing report
11	6/4	ID#1 - Shear key anchor bolts bottom (S1 & S2)
12	6/4	ID#2 - Shear key anchor bolts bottom (S3 & S4) & Pier 2 bearing bolts bottom housing (B1, B2, B3, B4)
13	6/4	ID#3 - Shear key anchor bolts top (S1 – S4))
14	6/4	ID#4 - Pier E2 bearing bolts – top housing (B1-B4)
15	6/4	ID#5 - Spherical bearing bushing assembly bolts
16	6/4	ID#6 - Bearing retainer ring plate assembly bolts
17	6/4	ID#7 - PWS strand anchor rods (main cable)
18	6/4	ID#8 - Tower saddle tie rods
19	6/4	ID#9 - Tower saddle turn rods
20	6/4	ID#10 - Tower saddle grillage bolts
21	6/4	ID#11 - Tower outrigger
22	6/4	ID#12 - Tower anchorage anchor bolts (75 mm dia.)

23	6/4	ID#13 -Tower anchorage anchor bolts (100 mm dia.)
24	6/4	ID#14 - East saddle anchor rods
25	6/4	ID#15 - East saddle tie rods
26	6/4	ID#16 - Cable bracket anchor rods
27	6/4	ID#17 - Bikepath anchor bolts at Pier W2
28	6/7	Townsend article on "Effects of Zinc Coatings on the Stress Corrosion Cracking and Hydrogen Embrittlement of Low-Alloy Steel
29	6/10	E-Mail from Rick Land to the FHWA Review Team – Bay Bridge – List of Experts Engaged (FYI)
30	6/11	Special Provisions 10-1.59, 10-1.60, 10-1.61; standard provision 75-1.05
31	6/11	Updated A354 Gr BD Rods installation status data sheet
32	6/11	Correspondence letter from Tennessee Galvanizing on tower anchor rods
33	6/18	TBPOC Bolt Report (draft)
34	6/25	SAS A354BD tests data summary table
35	6/28	SAS A354BD Testing Program Results (Test I, II, III)
36	7/8	Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge With Findings and Decisions, TBPOC, July 8, 2013
37	7/8	S1 & S2 New design updated plan set & special provisions

APPENDICES

A. Review of Caltrans Use of A354 BD Fasteners, June 2013
B. The Greg Assessment Tool, August 2013

APPENDIX A

REVIEW OF CALTRANS USE OF A354 BD FASTENERS – JUNE 2013

HOW DID DESIGNER ARRIVE AT ASTM A354 BD SPECIFICATION

The presumption being made in this background review is the SFOBB was designed in the early 2000's, likely conforming to the 1994 First Edition of the AASHTO *LRFD Bridge Design Specifications* (BDS). Understanding that some elements of the design may have changed through the construction of the bridge, some design consideration will be compared to the 2012 Sixth Edition of the LRFD BDS.

The 1994 BDS recognized two forms of high-strength fasteners, AASHTO M164/ASTM A325, and AASHTO M253/ASTM A490. From here on, these will only be referred to by their ASTM designations. The language in the 2012 BDS was essentially the same except for the addition of one sentence acknowledging "Anchor bolts shall conform to either ASTM A307 Grade C or ASTM F1554."

The major limitation with both the A325 and A490 specifications is they only cover fasteners with diameters ranging from ½ to 1-½ inches in diameter. Sometimes design constraints may require more area than a 1-½ inch diameter bolt can provide, and at times these may require materials with yield strengths in excess of 105 ksi, presumably, this is the case for the SFOBB as FHWA was not asked to review the design.

FHWA could not identify any direct reference to the ASTM A354 specification in any AASHTO documents relating to bridges. ASTM A354 is the *Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners*. In short, this specification provides a path to high-strength fasteners with diameters in excess of 1-½ inches. Within the 1997 A490 specification, there is a note provided in the first section of the specification saying:

> *"For quenched and tempered alloy steel bolts, studs, and other externally threaded fasteners with diameters greater than 1-½ inch, but with similar mechanical properties, refer to Grade BD of the Specification A354."*

This note does not appear in the 2008 version of the A490 specification, further historical investigation will have to be performed to determine which year the change occurred, though it appears about the time the SFOBB was designed, the A490 specification likely directed people to the A354 specification if similar strength levels were required at diameters in excess of 1-½ inches.

Considering no other design options existed to use lower strength anchors rods, Caltrans' decision to use the A354 BD specification is founded, as there is clear path through the ASTM specifications, at the time of design, to arrive at it.

CORROSION PROTECTION OF ASTM A354

The BDS allows for the hot-dip galvanizing of A325 bolts provided the galvanizing is performed according to the ASTM A153 specification and that they were tension tested after galvanization. The galvanization of A490 bolts was strictly prohibited and in the 1997 A490 specification, Article 5.4 clearly stated that:

> *"Protective Coatings – The bolts shall not be hot dip, mechanically, or electroplated with zinc or other metallic coatings as such bolts are subject to hydrogen embrittlement with subsequent stress corrosion cracking and delayed brittle failure in service. See Appendix X1 for additional information on hot dip zinc coatings."*

Appendix X1 then provided useful information regarding the strength levels susceptible to embrittlement and that the zinc coatings can lock in hydrogen leading to embrittlement of these fasteners.

To the contrary of the A490 specification, the A354 specification does allow for zinc coatings, either hot-dipped or mechanically deposited, despite the comparable hardness, strength, and chemistry requirements to A490. It is not clear why the prohibition of galvanizing was not carried through this specification as it was in A490. Both the 1997 and 2007 versions of A354 were reviewed, two interesting notes were present in both of them. First is a note in the first section, which says:

> *"NOTE 2—Quenched and tempered alloy steel bolts for structural steel joints up through 1-1/2 in. in diameter are covered in Specification A 490. Alloy steel bolts, studs, and other externally threaded fasteners (that is, heavy hex-structural bolts over 1-1/2 in., hex bolts, anchor bolts, and countersunk bolts) exhibiting similar mechanical properties to bolts conforming to Specification A 490 shall be covered by Grade BD of this specification.*
>
> *When bolts of Grade BD of this specification are considered for pretentioned applications in excess of 50 % of the bolt tensile strength, the additional requirements of head size, maximum tensile strength, nut size and strength, washer hardness, tests, and inspections contained in Specification A 490 should be carefully considered."*

Additionally in Article 4.4 referring to the zinc coatings, another useful note is published that says:

> *"NOTE 4 – Research conducted on bolts of similar material and manufacture indicates that hydrogen-stress cracking or stress cracking corrosion may occur on hot-dipped galvanized Grade BD bolts."*

When hot-dip galvanizing, the A354 specification refers to the procedures outlined in ASTM A153 "*Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware.*" This was referenced in the 1997 A354 Specification, and in the 2007 A354 Specification this had been changed to the ASTM F2329 Specification "*Standard Specification for Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners.*" Going back to the A153 Specification, a section within it was devoted to embrittlement specifically saying:

> *"Embrittlement is a potential condition of steel that is cold-worked, depending on such factors as the steel type (strength level, aging characteristics), thickness, degree of cold work, and galvanizing process. The galvanizer, the designer and the fabricator shall take precautions against embrittlement. The precautions to fabricate properly and prepare the material for galvanizing to prevent embrittlement are described in Practice A 143."*

The ASTM A143 Specification generally alerts to cold working and thermal treatment of products being susceptible to embrittlement. More importantly, it alerts users to the notion that the pickling operation prior to hot-dip galvanizing can be a source of hydrogen, and that for steels with yield strengths in excess of 150 ksi, should be abrasive cleaned in lieu of pickling.

The newer F2329 specification is more comprehensive than A153, outlining a prohibition of hot-dip galvanizing for material with hardness in excess of HRC 40, and also alerts to use of mechanical descaling in lieu of pickling.

As an interesting note, as of 2008, zinc coatings are now allowed for use on A490 bolts. The change was due to testing of proprietary zinc coatings on A490 bolts sponsored by the Research Council of Structural Connection (RCSC). Based on the RCSC research, a proprietary zinc/aluminum coating known under the trade name known as Dacromet was approved for use on A490 bolts. The specification covering this coating is ASTM F1136. In the 2008 A490 specification, the prohibition to zinc coatings was lifted and Article 4.3 was added which said:

> *"When a protective coating is required and specified, the bolts shall be coated with Zinc/Aluminum Corrosion Protective Coatings in accordance with Specification F1136, Grade 3."*

In the 2012 A490 Specification, this was further amended by also allowing ASTM F2833 coatings for A490 bolts, which go under the trade name Geomet.

CALTRANS SPECIFICATIONS FOR GALVANIZED A354 BD FASTENERS

The notebooks provided by Caltrans were reviewed covering the 2008 and 2010 Pier E2 anchor rods. The following are some key points identified by FHWA.

The Caltrans specifications for the A354 BD bolts only outlined the following:

- A354 BD fasteners shall conform to the requirements of ASTM Designation: A354.
- A354 BD fasteners shall be dry blast cleaned to SSPC-10 "near white blast cleaning."
- A354 BD fasteners shall be galvanized in conformance with ASTM Designation A123 for bolts, and A 153 for nuts and hardware. The galvanizing shall occur within four hours of dry blast cleaning.
- The contractor shall submit certified test reports showing the A354 BD fasteners conform to the provisions of ASTM A143.

In the third bullet above, the A123 specification sends you to A153 in terms of externally threaded fasteners, like the anchor rods and bolts; the reference to A123 appears to be benign. The A153 specification mainly covers coating thickness and its acceptance; however it does allude to the notion that if embrittlement is a concern, refer to the A143 specification. The A143 specification does note that the pickling operation in galvanizing can be a source of hydrogen leading to embrittlement, especially for steels with UTS in excess of 150 ksi. In these situations, it recommends abrasive blast cleaning in lieu of pickling, and based on the second bullet above, Caltrans had this concern and did take this precaution in their specifications.

The fourth bullet above alerts to Caltrans knowledge of ASTM specifications regarding galvanizing and embrittlement. The testing requirements outlined in A143 call for a bend test described as follows:

> *A bend test for embrittlement of galvanized steel hardware such as bolts, pole and tower steps, braces, rods, reinforcing bars, etc., consists of bending the article and comparing the degree of bending to that which is obtained on a similar ungalvanized article. The article, before and after galvanizing, may be clamped in a vise and using a lever if necessary, bent until cracking of the base steel occurs, or to 90° whichever is less. The galvanized article should withstand a degree of bending substantially the same as the ungalvanized article. Flaking or spalling of the galvanized coating is not to be construed as an embrittlement failure. For threaded articles, the test shall be made on the unthreaded portion.*

This article remained pretty much the same in the time period between design and construction of the SFOBB. Additionally, A143 outlines for hot-dipped galvanized externally threaded fasteners, an alternate embrittlement test in F606 may be used. The F606 testing comprises of tensioning a threaded fastener between non-parallel surfaces, the so-called "wedge test". When tensioning the bolt, the nut would be forced to bend the rod. However, the slope of the wedge is only specified for fasteners up to 1-½ inches in diameter. The Caltrans specification left the discretion of the testing to the Contractor (American Bridge-Fluor). Admittedly, the bend test would be difficult to perform on the 3 to 4 inch diameter rods, but it is possible. The Contractor would likely dismiss the wedge test because of the diameter limitation, though this test would be much easier to conduct in a mock-up since the Contractor would have the tensioning equipment. FHWA could not find any evidence that the Contractor provided any evidence that the rods meeting all the conformance provisions of A143, either through a bend test, or wedge test, or an RFI asking to neglect the provision.

QUALITY CONTROL AND ACCEPTANCE OF GALVANIZED A354 BD FASTENERS

In review of the 2008 and 2010 notebooks, Caltrans did perform quality control by sending randomly selected rod assemblies and material samples to external labs for testing. This testing was small scale consisting of 0.505 inch diameter specimens turned from the larger rods. It is unlikely that this small testing would have identified any embrittlement issues because according to the referenced A370 testing specification, the sample is removed from the larger bar, half way between the center and the surface. Most of the hardenability and embrittled region would be near the surface and not captured in this type of testing.

In the 2008 report, it appears that Caltrans did perform internal testing of complete assemblies for nine anchors. Many of these were considered "invalid" for determining the yield strength, though all tests broke the rod at a force between 920 and 960 kips of force (UTS of 154 to 160 ksi). All were noted to have "broke in bar; necking okay". No testing of complete assemblies could be found in the 2010 notebook. This type of testing could have uncovered any internal hydrogen embrittlement issues, though it was not performed on every lot.

LESSONS LEARNED

The original bridge designer only intended for the A354 BD fasteners to have an ultimate tensile strength (UTS) of 140 ksi, which comes directly from the A354 specification minimum UTS requirement. However, many of the real yield strengths way exceeded this this assumed tensile strength. Future uses of the A354 standard should provide supplementary provisions specifying contractors to develop a heat treatment schedule that would result in a material with a UTS closer to the specification minimum or imposed a range on the UTS, rather than just a minimum. This should mitigate getting extremely hard or high-strength material with increased susceptibility to embrittlement or stress corrosion cracking. The lesson learned is stronger material is not necessarily better in all situations.

Close attention should be given when specifying quality assurance testing that merely references ASTM specifications. At times, engineering judgment is required to adapt ASTM specification for a particular use. As was identified above, there may be gaps between various ASTM specification and special provisions may have to be written to bridge those gaps. In future applications of fasteners over 1-1/2 inches in diameter, consideration should be given to specifying bending or wedge testing and who is responsible for conducting it, particularly for galvanized fasteners. This was an identified gap between the ASTM A143 and F606 specifications.

While and expensive option, consideration should be given to randomized full-scale fastener testing of very large diameter fasteners in future infrastructure projects. ASTM protocols target specific metrics for materials, often derived from tests on portions of a complete assembly. Large diameter, galvanized fasteners can suffer from poor machining, heat treatment and improper hot-dipping procedures. The conventional ASTM tests tend to sample material away from the surface of the fastener where most problems would originate from. A full-scale test of a fastener encompasses potential problems into one test, and there is little to argue about in its results leading it to be the ideal check on quality.

APPENDIX B

Explanation of the Chart Showing Risk of Susceptibility for Stress Corrosion Cracking for the Galvanized ASTM A354 Grade BD Bolts/Rods on the San Francisco-Oakland Bay Bridge Self Anchoring Suspension Span

This chart looks at these risk categories including environmental conditions, accessibility, applied tension, Rockwell hardness, redundancy, measured tensile strength, and Charpy V-notch toughness values to determine an overall risk for stress corrosion cracking of the Galvanized A354 Grade BD bolts/rods used on the Self-anchoring Suspension (SAS) span.

There are 2,306 galvanized ASTM A354 Grade BD bolts/rods on the SAS at 17 different locations. Some of the bolts/rods are exposed to the weather and must endure the damp conditions of the Bay Area weather while others can be sheltered from the weather and moisture can be controlled through dehumidification.

Some of the bolts/rods cannot be accessed for inspection, maintenance, or replacement activities. Two examples of accessibility issues are:

- The Pier E2 shear keys S1 and S2 anchor rods supplied in 2008 are dead ended within the concrete pier leaving no option for direct replacement, nor inspection of the dead end of the anchor rod.
- The Pier E2 bearings and shear keys S3 and S4 anchor rods supplied in 2010 have good accessibility for inspection, maintenance, and replacement because these are through anchor rods and can be inspected and replaced.

The environment and accessibility risk categories are combined and four parameter limit definitions are defined as:

- Severe – is when the bolts/rods are fully exposed to the Bay Area moisture and access for monitoring (inspection), maintenance, and replacement is not possible.
- High – is when the bolts/rods are fully exposed to the Bay Area moisture and access for inspection, maintenance, and replacement is possible.
- Moderate – is when the bolts/rods are sheltered and in dehumidified zones however access to inspect, maintain, or replace is not possible.
- Low – is when the bolts/rods are sheltered and in dehumidified zones and fully accessible to inspect, maintain, or replace.

The remaining five risk categories use parameter definitions for high, moderate, and low risk. Each of the risk categories have parameter limits defined based on our review findings.

Table 1: Risk Category Parameter Limit Definitions

Applied Tension (% Fu)	Rockwell Hardness	Redundancy per location	Ultimate Tensile Strength (ksi)	Charpy V-notch Toughness 40oF
High ≥ 50	High >36	High <10	High > 160	High ≤ 20.0
Moderate < 50 and ≥ 25	Moderate is 35 or 36	Moderate < 30 and ≥ 10	Moderate ≤ 160 and >150	Moderate ≤ 35.0 and > 20.0
Low < 25	Low ≤ 34	Low ≥ 30	Low ≤ 150	Low > 35.0

Next we placed different weights on these six different risk categories leaning heavier on the environment and accessibility, the hardness values, and the applied tension values as these directly affect susceptibility for stress corrosion cracking (SCC). Redundancy, average measured tensile strength, and toughness values received reduced weights. There were six bolt/rod locations that did not have Charpy Toughness values as they were not tested so a factor of 1 was used in the risk evaluation.

Table 2: Risk Category Weighting Factors					
Environment and Access	**Applied Tension**	**Ave. Rockwell Hardness**	**Redundancy**	**Ave. Tensile Strength**	**Ave. Charpy Toughness**
2.5	N/A	N/A	N/A	N/A	N/A
2.0	2.0	2.0	1.5	1.5	1.5
1.5	1.5	1.5	1.0	1.25	1.25
1.0	1.0	1.0	0.5	0.75	0.75

First, a risk level is assigned for each of the six categories and the 17 bolt/rod locations based on the criteria in Table 1 and the textual description of environmental/access risk. The next step was to assign a numerical score to each risk level based on the weighting factors described in Table 2. The sum of all the weights define an overall risk category according to the following:

Summed Weights	Severe	High	Moderate	Low
Parameters	>9	≤ 9 and ≥ 8.25	> 8.25 and ≤7.25	< 7.25

The final step was to sum the six weighting factors for each bolt/rod location to attain an overall score assigned to the 17 bolt/rod locations and are summarized in Table 3.

Table 3: Risk Assessment for the SAS Galvanized A354 Grade BD Bolts/Rods to SCC			
Location Description	**Bolt/Rod Group Locations**	**Bolt/Rod Description**	**Overall Risk for SCC Rating**
Pier E2 Cap	1	Shear Key (S1, S2)	Severe
Pier E2 Cap	2	Elements (S3, S4) (B1-4)	Moderate
Pier E2 Top	3	Shear Key (S1-S4)	High
Pier E2 Top	4	Bearing (B1-B4)	High
Pier E2 Bearing	5	Bearing Bushings (B1-B4)	High
Pier E2 Bearing	6	Bearing Retaining Rings (B1-B4)	High
Cable Anchorage	7	PWS Anchor Rods and Sockets	Low
Tower Top	8	Saddle Ties	High
Tower Top	9	Saddle Segment Splices	Low
Tower Top	10	Saddle Grillage Anchor	Low
Tower Top	11	Maintenance Jib Crane	High
Tower Bottom	12	Cap Anchors	Low
Tower Bottom	13	Cap Anchors	Low
East Splay Saddles	14	Anchors	Moderate
East Splay Saddles	15	Saddle Ties	Low
East Cable	16	Strong Back Anchors	High
Pier W2	17	Bike Path Anchor	Moderate

Attached is a print of the Excel spreadsheet used to perform the risk assessment calculations.

Attachment

Risk of Susceptibility for Stress Corrosion Cracking for the Galvanized ASTM A354 Grade BD Bolts/Rods on the San Francisco-Oakland Bay Bridge Self Anchoring Suspension Span

Location	Grp	Description	Type	Thread	Diameter (Inch)	Length (Foot)	Qty	Environment	Access	Risk Environment	Tensioning	Design Percent Fu	Risk Applied Tension	Hardness	Risk Hardness	Redundancy	Risk Redundancy	Avg. Tensile Strength (ksi)	Risk Avg. Tensile Strength	Average CVN @ 40F	Risk Ave. CVN @ 40F	Weighted Values	Overall Category
Pier E2 Cap	1	Shear Key (S1, S2)	Rod	Cut	3	17.2	60	Exposed	No	Severe	Tension	70	High	37	High	30	Low	165.5	High	13.5	High	10	Severe
Pier E2 Cap	1	Shear Key (S1, S2)	Rod	Cut	3	10	36	Exposed	No	Severe	Tension	70	High	37	High	18	Low	165.5	High	13.5	High	10	Severe
Pier E2 Cap	2	Shear Key (S3, S4)	Rod	Cut	3	21.9	96	Exposed	Yes	High	Tension	70	High	34	Low	48	Low	156.2	Moderate	37.2	Low	7.5	Moderate
Pier E2 Cap	2	Bearing (B1-B4)	Rod	Cut	3	22.6	64	Exposed	Yes	High	Tension	70	High	34	Low	16	Low	156.2	Moderate	37.2	Low	7.5	Moderate
Pier E2 Cap	2	Bearing (B1-B4)	Rod	Cut	3	22.2	32	Exposed	Yes	High	Tension	70	High	34	Low	8	Low	156.2	Moderate	37.2	Low	7.5	Moderate
Pier E2 Top	3	Shear Key (S1, S2)	Rod	Cut	3	4.4	96	Exposed	Yes	High	Tension	70	High	35	Moderate	48	Low	162.6	High	36.9	Low	8.25	High
Pier E2 Top	3	Shear Key (S1, S2)	Rod	Cut	3	1.8	64	Exposed	Yes	High	Tension	70	High	35	Moderate	32	Low	162.6	High	36.9	Low	8.25	High
Pier E2 Top	3	Shear Key (S3, S4)	Rod	Cut	3	4.3	96	Exposed	Yes	High	Tension	70	High	35	Moderate	48	Low	162.6	High	36.9	Low	8.25	High
Pier E2 Top	3	Shear Key (S3, S4)	Rod	Cut	3	1.7	64	Exposed	Yes	High	Tension	70	High	35	Moderate	32	Low	162.6	High	36.9	Low	8.25	High
Pier E2 Top	4	Bearing (B1-B4)	Rod	Cut	2	3.6	224	Exposed	Yes	High	Tension	70	High	35	Moderate	56	Low	162.6	High	26.7	Moderate	8.75	High
Pier E2 Bearing	5	Bearing Bushings (B1-B4)	Rod	Cut	1	2.4	96	Exposed	No	Severe	Tension	61	High	34	Low	24	Moderate	162.5	High	N/A		9	High
Pier E2 Bearing	6	Bearing Retaining Rings (B1-B4)	Cap Screw	Cut	1	0.2	336	Exposed	No	Severe	Snug + ¼ Turn	40	Moderate	35	Moderate	84	Low	175.3	High	N/A		8.5	High
Cable Anchorage	7	PWS Anchor Rods and Sockets	Rod	55 Cut & 219 Rolled	3.5	27.1 to 31.8	274	Dehumidified	Yes	Low	Load Transfer (4 stages)	35	Moderate	36	Moderate	137	Low	151.9	Moderate	39	Low	6.5	Low
Tower Top	8	Saddle Ties	Rod	Rolled	4	6.0 to 17.5	25	Dehumidified	Yes	Low	Tension	68	High	35	Moderate	25	Moderate	164.8	High	16.8	High	8.5	High
Tower Top	9	Saddle Segment Splices	Rod	Cut	3	1.5	100	Dehumidified	Yes	Low	Tension	45	Moderate	37	High	100	Low	148.2	Low	52.3	Low	6.5	Low
Tower Top	9	Saddle Segment Splices	Rod	Cut	3	1.4	8	Dehumidified	Yes	Low	Snug	1	Low	37	High	8	Low	148.2	Low	13	High	6.75	Low
Tower Top	10	Saddle Grillage Anchor	Bolt	Cut	3	1.2	90	Exposed	Yes	High	Snug	1	Low	34	Low	90	Low	150.6	Moderate	N/A		6.75	Low
Tower Top	11	Maintenance Jib Crane	Bolt	Cut	3	2.1	4	Exposed	Yes	High	Snug	1	Low	39	High	4	High	158.4	Moderate	N/A		8.75	High
Tower Bottom	12	Cap Anchors	Rod	Cut	3	25.6	388	Dehumidified	No	Moderate	after load transfer)	48	Moderate	34	Low	97	Low	160.0	Moderate	40.5	Low	6.5	Low
Tower Bottom	13	Cap Anchors	Rod	Cut	4	25.7	36	Dehumidified	No	Moderate	Tension (before and after load transfer)	37	Moderate	33	Low	9	Low	154.2	Moderate	31.7	Moderate	7	Low
East Splay Saddles	14	Anchors	Rod	Cut	2	2.6	32	Dehumidified	No	Moderate	Snug	1	Low	37	High	16	Moderate	157.1	Moderate	27	Moderate	8	Moderate
East Splay Saddles	15	Saddle Ties	Bolt	Cut	3	4.7	18	Dehumidified	Yes	Low	Snug	1	Low	33	Low	9	High	146.2	Low	17.8	High	6.75	Low
East Cable	16	Strong Back Anchors	Rod	Rolled	3	10.3 to 11.1	24	Exposed	Yes	High	Tension	18	Low	36	Moderate	4	High	154.5	Moderate	N/A		8.25	High
Pier W2	17	Bikepath Anchor	Rod	Cut	Metric) $1\text{-}^{3}/_{16}$	1.5	43	Exposed	Yes	High	Snug	1	Low	36	Moderate	43	Low	171.5	High	N/A		7.5	Moderate
			Total SAS Galvanized A354 Grade BD:				2306																

Risk Category Parameter Limit Definitions:

Environment and Access	Applied Tension	Rockwell Hardness	Redundancy	Tensile Strength	Average Charpy V-Notch	Overall Rating
Severe - Exposed and access limited	N/A (NOTE snug tight is 1.)	N/A	N/A	N/A	N/A (NOTE: No Test-Overall+1.)	Severe - >9
High - Exposed and can be accessed	High - Applied tension ≥ 50% Fu	High - Rockwell is >36	High - < 10 per location	High - > 160.0	High - < 20.0	High - ≤ 9 and ≥ 8.25
Moderate - Dehumidified and access limited	Moderate - Applied tension < 50% and ≥ 25% Fu	Moderate - Rockwell is 35 or 36	Moderate - < 30 and ≥ 10 per location	Moderate - ≤ 160.0 and > 150.0	Moderate - ≤ 35.0 and >20.0	Moderate - <8.25 and ≥7.5
Low - Dehumidifed and can be accessed	Low - Applied tension < 25% Fu	Low - Rockwell is ≤34	Low - ≥ 30 per location	Low - ≤ 150.0	Low - >35.0	Low - < 7.5

Weights	Environment & Access	Applied Tension	Hardness	Redundancy	Tensile Strength	Toughness
Severe	2.5	n/a	n/a	n/a	n/a	n/a
High	2	2	2	1.5	1.5	1.5
Moderate	1.5	1.5	1.5	1	1.25	1.25
Low	1	1	1	0.5	0.75	0.75