VALIDITY OF CALTRANS’ ENVIRONMENTAL HYDROGEN EMBRITTLEMENT TESTS ON GRADE BD ANCHOR RODS IN THE SAS SPAN

Test IV Rig for Full-length Bridge Rods
VALIDITY OF CALTRANS’ ENVIRONMENTAL HYDROGEN EMBRITTLEMENT TESTS ON GRADE BD ANCHOR RODS IN THE SAS SPAN

December 2, 2014

Prepared for

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TOLL BRIDGE PROGRAM OVERSIGHT COMMITTEE (TBPOC)

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VALIDITY OF CALTRANS’ ENVIRONMENTAL HYDROGEN EMBRITTLEMENT TESTS ON GRADE BD ANCHOR RODS IN THE SAS SPAN

ABSTRACT

The California Department of Transportation (Caltrans) opened the new East Span of the San Francisco-Oakland Bay Bridge in September 2013. Six months before the opening, 32 of the 96 anchor rods, 3 inches in diameter, for two shear keys (S1 and S2) on Pier E2, failed during the first two weeks after they were pretensioned to 0.7Fu or 98 ksi. These anchor rods conformed to ASTM A354, Grade BD, hot dip galvanized (HDG). The cause of the failures: environmental hydrogen embrittlement (EHE). The self-anchored-suspension (SAS) span of the East Span now has 2,210 HDG BD rods, since the 96 HDG BD rods for S1 and S2 were abandoned. The structural integrity of the SAS depends on 723 HDG BD rods, 3 to 4 inches in diameter, each weighing 1,000 pounds or more.

Caltrans conducted a large scale test program on the HDG BD rods in the SAS over the last 18 months. Caltrans’ test program ranged from in-situ hardness tests of over 1,000 installed HDG BD rods to EHE (or SCC) tests, using HDG BD rods as specimens, and other tests. It cost $20 million, which is in addition to the $25 million expended to fix S1 and S2 to the E2 cap beam using steel tendons and concrete jackets.

Caltrans concluded that all the 2,210 HDG BD rods in the SAS are “safe” as installed from future EHE failures. Based on their interpretation of the EHE test data, they concluded that a conservative EHE threshold load is 0.75Fu (or 105 ksi) for all HDG BD rods in the SAS. They believe the 0.75Fu provides a 0.05Fu (or 7% or about 7%) safety margin because the HDG BD rods in the SAS are pretensioned to 0.70Fu (98 ksi) maximum.

Since the 0.05Fu (or 7%) safety margin appeared unreasonably small to account for various factors that are difficult to predict precisely and could be even less than probable errors of Caltrans’ EHE tests and rod pretensioning, Caltrans test protocols, test data, and data interpretation have been reviewed.

This review revealed that Caltrans’ EHE test protocols and data interpretation are both problematic and unscientific and that their conclusions as to the integrity of the SAS could not be supported. Reasons why the 0.75Fu EHE threshold stress will not resolve possible EHE failures of HDG BD rods in the SAS have been discussed. Rather than relying on the EHE threshold stress strategy, Caltrans should replace the HDG BD rods that are susceptible to EHE failures with new HDG BD rods that are not susceptible or at least more resistant to EHE failures wherever possible.

A separate plan would be required for the tower base anchor rods, which are not replaceable. Some of the tower base anchor rods may eventually fail due to EHE, particularly in the event seawater permeates through the concrete to their bottom ends in the footing box of the tower foundation. Caltrans should continuously monitor their performance and develop a risk analysis of their eventual failures.
VALIDITY OF CALTRANS’ ENVIRONMENTAL HYDROGEN EMBRITTLEMENT TESTS ON GRADE BD ANCHOR RODS IN THE SAS SPAN

EXECUTIVE SUMMARY

The San Francisco-Oakland Bay Bridge (SFOBB) was closed for a month of repair of the East Span, following the 1989 earthquake damage. The new East Span construction began in 2002. After 11 years of construction and $6.4 billion, it was opened to traffic in September 2013. Six months before the opening, 32 of the 96 large anchor rods for two shear keys (S1 and S2) failed on Pier E2, the east end of the Self-Anchored Suspension (SAS) Span. Shear keys are large steel castings of seismic stabilizers. The 96 anchor rods were part of 2,306 hot dip galvanized (HDG) anchor rods, conforming to ASTM A354, Grade BD. The 32 HDG BD rods failed due to environmental hydrogen embrittlement (EHE). The integrity of the SAS depends on 723 HDG BD rods, 3 to 4 inches in diameter, each about 1,000 pounds or more.

The California Department of Transportation (Caltrans), the owner and operator of the SFOBB, embarked on a massive test program to resolve the concerns about possible EHE failures of the remaining 2,210 HDG BD rods in the SAS. It ranged from in-situ field hardness testing of installed HDG BD rods to EHE (or SCC) testing, using 2 to 4 inch diameter full size HDG BD rods as specimens. The rod specimens, without precracks, were incrementally loaded in 432 hours up to 0.80Fu in 9 steps. Fu is the specified minimum tensile strength for Grade BD or 140 ksi for most cases. A small saltwater (3.5%NaCl) chamber enclosed the threads at the nut engagements on both ends. If not failed in 432 hours, the load was increased to 0.85Fu and held for 140 hours. If not failed still, the rod specimens were monotonically loaded to failure.

The use of 2 to 4 inch diameter HDG high strength steel rods as specimens for EHE threshold stress determination is unprecedented according to Caltrans. This was augmented by another EHE test, using small specimens, similar in size to CVN (Charpy V-notch) toughness specimens, in 3.5% NaCl solution, conforming to ASTM F1624.

Caltrans released a draft report on the results of these tests over the past 18 months, costing $20 million. Caltrans and its contractors, including the Engineer of Record, concluded: (1) a conservative EHE threshold stress is 0.75Fu (105 ksi) for all the HDG BD rods in the SAS span, and (2) all of them are “safe” as installed from future EHE failures since they are pretensioned to 0.10 – 0.70Fu (14 – 98 ksi).

The mere 0.05Fu (7 ksi or about 7%) margin appears insufficient as a safety factor. To check the validity of the above conclusions, Caltrans’ EHE test protocols, test data, and conclusions and recommendations reached by Caltrans have been reviewed.

The results of this review indicate that the EHE test protocols were scientifically problematic and the findings and conclusions that the HDG BD rods in the SAS are “safe” were based on questionable data interpretation. The possibility of EHE failures of critical HDG BD rods in the SAS remains unresolved. Several reasons why the conclusions by Caltrans and their consultants could be incorrect have been discussed.

Caltrans’ EHE test program was not conceptually astute. A pretension control as a means of avoiding EHE failures in HDG BD rods that are susceptible to HE cracking will not work consistently in field
applications. Caltrans’ EHE test protocols on using the gigantic HDG BD rods as specimens appeared commendable but involved many pitfalls. Therefore, Caltrans should not try to redo the HDG BD rod EHE tests using modified or “improved” protocols. Caltrans should abandon the EHE test scheme altogether.

Several reasons why Caltrans should pursue an alternative strategy of resolving the EHE failure potentials of HDG BD rods in the SAS span have been discussed. Caltrans needs to identify the HDG BD rods that are susceptible to EHE failures and replace them with new HDG BD rods with hardness limitations that have been proven not susceptible or resistant to HE cracking in marine atmospheric services. This would be more technically justifiable and probably more cost effective in the long run than relying on EHE threshold stress data that were generated by “unprecedented” test protocols that have not been validated as scientifically acceptable. Also, no painting systems, recommended by Caltrans as a deterrent to EHE failures of HDG BD rods, will work, particularly in restricted space around the installed HDG BD rods, raising their “long term capacity” to 1.0Fu or greater as claimed by Caltrans.

The 424 tower base anchor rods are not replaceable. The reasons why some of them could eventually fail due to EHE, particularly in the event seawater permeates through the concrete to the bottom ends of the 26 ft long anchor rods in the footing box, are discussed. Instead of keeping them protected from corrosion by air dehumidification, a recent inspection revealed 95% of the 424 tower base anchor rods in a wet condition and one-third of them in a not fully grouted condition since installation sometime before 2011. In preparation of the eventual EHE failures of some of them, Caltrans should conduct a risk analysis, including a preparatory remedial design to secure the tower.
List of Reviewers

The following professors, consultants, and engineers have reviewed this report and provided comments. Each of them did so as an individual, not as a representative of their organizations.

<table>
<thead>
<tr>
<th></th>
<th>Names</th>
<th>Job Title/Affiliation</th>
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<tbody>
<tr>
<td>1</td>
<td>Robert G. Bea, Ph.D.</td>
<td>Professor Emeritus, Civil and Environmental Engineering</td>
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<td></td>
<td>University of California, Berkeley</td>
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<td>2</td>
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<td>President of iCorrosion LLC</td>
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<td>3</td>
<td>Harold J. Mantle, P.E.</td>
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<td>Pierre R. Roberge, Ph.D., P.E.</td>
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</tr>
</tbody>
</table>
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>EXECUTIVE SUMMARY</th>
<th>List of Reviewers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>EXECUTIVE SUMMARY</th>
<th>List of Reviewers</th>
</tr>
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<tbody>
<tr>
<td>i</td>
<td>i</td>
<td>iv</td>
</tr>
</tbody>
</table>

## 1.0 INTRODUCTION

### 2.0 HYDROGEN EMBRITTLEMENT CRACKING OF HDG BD RODS IN THE SAS SPAN

### 3.0 CALTRANS’ HDG BD ROD TESTS FOR HYDROGEN EMBRITTLEMENT PREVENTION

3.1 Tests I – VI, Caltrans’ Grade BD Anchor Rod EHE Failure Prevention Program

3.2 Caltrans’ S1 and S2 Rod Specimens

3.3 Test I and II - Hardness and Other Lab Tests

3.4 Test III - Tensile Properties

3.5 Tests IV – VI Stress Corrosion (Environmental Hydrogen Embrittlement) Cracking Tests

3.5.1 Test IV – Townsend Test to Determine EHE Threshold Stresses for HDG BD Rods in the SAS

3.5.2 Tests V (Raymond Test) - Incremental Step Loading Test (ASTM F1624)

3.5.3 Test VI (Gorman Test) – Slow Strain Rate Test

## 4.0 EVALUATION OF CALTRANS TEST IV PROTOCOLS AND DATA

4.1 Caltrans’ EHE Threshold Stresses Data – Inconsistent and Invalid

4.2 Pretension Level Control – A Wrong EHE Prevention Methodology

4.3 Validity of Test IV Protocols for Determining EHE Threshold Stresses for HDG BD Rods

4.3.1 Test IV Protocol Validity: Invalid

4.3.2 Error-filled Data Presentation and Questionable Test Data

4.3.3 More Errors

4.3.4 Comparison of Test IV Data with 1975 Townsend Data

4.3.5 Probable Reasons for Caltrans’ Anomalous EHE Threshold Stress Data

4.4 Caltrans Remedial Action

## 5.0 LIMITATION OF TESTS V – VI, SMALL SPECIMEN TESTS

5.1 Limitation of Fatigue Precracked Specimen K_EHE Tests

5.2 Unreasonable Test V Data from Specimens without Precracks

## 6.0 LITMUS TESTS FOR 0.75Fu AS EHE THRESHOLD STRESS FOR HDG BD RODS

## 7.0 ALTERNATIVE STRATEGY TO TESTS IV AND V

7.1 Use of High Strength Steel Rods Not Susceptible to EHE Cracking

7.2 Risk Analysis of Tower Base Anchor Rods

## 8.0 CONCLUSIONS AND RECOMMENDATIONS

Appendices A - C

<table>
<thead>
<tr>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
</tr>
<tr>
<td>ii</td>
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<td>42</td>
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<td>46</td>
</tr>
<tr>
<td>48 - 53</td>
</tr>
</tbody>
</table>
VALIDITY OF CALTRANS’ ENVIRONMENTAL HYDROGEN EMBRITTLEMENT TESTS ON GRADE BD ANCHOR RODS IN THE SAS SPAN

1.0 INTRODUCTION

The California Department of Transportation (Caltrans) had the new east span of the San Francisco-Oakland Bay Bridge (SFOBB) constructed and opened to traffic in September 2013. It replaced the old east span, which was damaged during the 1989 earthquake. The new SFOBB will look like that in Figure 1 in about two years when the old East Span in Figure 2 has been demolished and completely removed.

Figure 1 The San Francisco-Oakland Bay Bridge (est. 2016).

The new East Span, 2.2 mile long, comprises the Skyway and the Self-Anchored-Suspension (SAS) span. The former consists of 452 precast concrete segments and latter orthotropic box girder (OBG) steel decks. “The SAS, at 2,047 feet, is the world’s longest [and the widest] SAS and the signature element of the new East Span.” It is held up by a single tower (T1), a single 31 inch diameter continuous steel cable of 137 parallel wire strands (PWS), two piers (E2 and W2), and 2,306 high strength steel anchor rods (Appendix A). All are straight round steel rods with both ends threaded for nut engagements. These anchor rods conform to ASTM A354, Grade BD, hot dip galvanized (HDG).

1 http://baybridgeinfo.org/projects/sas  If baybridgeinfo.org does not open, copy the URL, paste it on a Word doc, and click.
Figure 2 identifies the locations of the 723 anchor rods that are critical to the integrity of the SAS. They are 3 to 4 inches in diameter by up to 32 ft in length. A 3½ inch diameter PWS anchor rod or a 4 inch diameter tower base anchor rod would weigh more than 1,000 pounds each.

In March 2013, six months before the scheduled opening of the new East Span to traffic, 32 of the 96 HDG BD rods for shear keys S1 and S2 failed under static load in the first two weeks after they were pretensioned to 0.7Fu (98 ksi). These HDG BD rods were 3 inches in diameter by up to 17 ft in length, weighing up to 400 lbs each. All 32 failures occurred in the bottom threads, which had been exposed to pools of standing water in grout pipes for five years because of construction schedule delays before they were pretensioned.

S1 and S2 are part of the four shear keys (S1 – S4) and four bearings (B1 – B4). They are large steel castings, installed as “seismic stabilizers” between the cap beam of Pier E2 and the east ends of the OBG steel road decks of the SAS span. The cause of the failures of the 3 inch HDG BD rods for S1 and S2 base plates under static tension was identified as hydrogen embrittlement (HE) or more specifically as environmental hydrogen embrittlement (EHE). 4,5,6,7

Because the bottom threads of the 96 HDG BD rods for S1 and S2 were inaccessible and there was not enough head space for replacement with new rods, the base plates of S1 and S2 had to be “clamped” down to the Pier E2 cap beam using steel tendons that were encased in steel saddles. The steel tendons were anchored in new concrete jackets on both sides of the cap beam. The clamping capacity of the 64 unfailed rods was abandoned. This remediation design for S1 and S2 was approved by civil engineering experts and by the Federal Highway Administration (FHWA). The repair (or a “retrofit” as referred to by Caltrans), necessitated by the 32 HDG BD rod failures, cost $25 million.

To make certain no additional EHE failures would occur in the remaining 2,210 HDG BD rods in the SAS span, Caltrans has conducted massive amounts of tests including EHE (or Stress Corrosion Cracking - SCC) tests during the last year and half, expending some additional $20 million.

Caltrans issued a draft report on the HDG BD rod evaluation.8 It concluded that the 32 HDG BD rods failed because the 96 HDG BD rods for S1 and S2, produced in 2008, had “higher than normal susceptibility” to HE cracking (based mainly on low Charpy V-notch (CVN) toughness values of failed rods) and all the remaining 2,210 HDG BD rods in the SAS span are “safe” from future EHE failures.

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3 Fu represents the minimum specified tensile strength, which is 140 ksi in the case of Grade BD for sizes > 2½ inches.
5 S. Brahimi et al: Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6 http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_H_Other_Documents/H13%20E2_Shear_Key_Rod_Failure_Frac ture_Analysis_Report.pdf
7 TBPOC: Toll Bridge Program Oversight Committee was established in 2005 by the California Legislature as the top decision maker of the East Span project.
8 Because References 5 and 6 were unclear regarding the cause of the S1 and S2 anchor rod failures as to environmental hydrogen embrittlement (EHE), Chung and Thomas presented the following (unsolicited) reports, in which they explained why the rod failures were due to EHE. Y. Chung and L. K. Thomas: High Strength Steel Anchor Rod Problems on the New Bay Bridge, Rev. 1, November 12, 2013, Prepared (unsolicited) for Senator Mark DeSaulnier, Committee on Transportation and Housing, California State Senate. http://docdroid.net/dxzl
during the 150 year design life of the SAS span. According to Caltrans, there is a 0.05Fu (7 ksi or 7\%) margin between the 0.10 – 0.70Fu pretension level for all HDG BD rods in the SAS and their EHE threshold stress, which is 0.75Fu according to Caltrans.

The above conclusion by Caltrans appears, however, erroneous and misleading. Firstly, the 7\% margin is simply not enough to cover even the probable errors of the EHE tests and variations in axial stresses in long HDG BD rods after pretensioning. Referring to the stress distribution in pretensioned (or preloaded) bolts, Bickford stated, “There is now no such thing as ‘uniform stress level,’ even in the body.” The pretension level in terms of 0.1 – 0.70Fu does not take the stress concentration effects, for example on the roots of the rod threads engaged by the nuts, into account. It will be also unrealistic to expect HDG BD rods that are as long as 26 ft (tower base) and 32 ft (PWS anchor rods) to be perfectly straight and line up perfectly during installation. Some eccentric loading alone in some rods may cause load variations of as much as or more than 0.05Fu. Otherwise, Caltrans needs to show the probable errors of HDG BD rod pretensioning and of the “unprecedented EHE threshold stress determination tests” are less than 0.05Fu or less than 7\%.

Caltrans test data do not support the above optimistic conclusion as will be discussed later. The validity of the Caltrans EHE test protocols is questionable and may be invalid; their data interpretation is erroneous. Caltrans needs to clarify many uncertainties, discussed in this review, before their conclusions and recommendations may be considered technically justifiable and acceptable.

While Caltrans repeatedly emphasized that their EHE test program was “unprecedented,” the data it generated is of questionable value since many of the tests are simply “bad tests” as will be discussed later. It is as unprecedented as the selection of the gigantic (3 to 4 inch diameter) HDG BD rods without “a careful evaluation.” The EHE failures of the shear key anchor rods, the $25 million retrofit, and the $20 million EHE tests could have been avoided if Caltrans had done “a careful evaluation” of BD rods required by Caltrans’ own bridge design specifications.\(^9\)

The purpose of this report is to review the Caltrans EHE test protocols for validity, evaluate their test data, including hardness and tensile property data, point out inconsistencies and errors, discuss why the conclusions and recommendations by Caltrans may be invalid or why Caltrans needs to provide more explanations/technical justifications for the EHE test protocols and data interpretations. Also, the reasons why Caltrans should pursue a different strategy than relying on the rod pretension levels in resolving the potential HDG BD rod failures in the SAS span are discussed.

It would be important for the bolting industry as well as for the (bridge) engineering/construction industry to have a correct understanding of EHE failures of large diameter HDG BD rods and remedies. Caltrans has expended an “unprecedented” amount of work and expenditure to understand their failures due to EHE during service for the new bridge with a 150 year design life over seawater. It would be of utmost importance that their test protocols and data interpretation be subjected to scientific scrutiny to see if what Caltrans has been doing and how they have interpreted the test results are scientifically acceptable.

It is important that Caltrans EHE protocols and test data interpretations are both technically correct and clearly understandable not only by technical experts but also by most engineers. The integrity of the SAS rides on the correctness of Caltrans’ EHE test data and their interpretation. Therefore, it is important to

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have Caltrans report reviewed independently by “outsiders” without conflicts of interest. This is what this report aims to achieve.

Unfortunately, this review has revealed many signs that the EHE test protocols and data interpretations by Caltrans may be flawed, leading to conclusions and recommendations that may be not optimum or could be incorrect.

2.0 HYDROGEN EMBRITTLEMENT CRACKING OF HDG BD RODS IN THE SAS SPAN

Hydrogen embrittlement (HE) as a metal cracking mechanism has been well established since around the 1970’s. At room temperature, HE is one of the most significant factors that put the upper bound design stress limits for carbon and low alloy steels (e.g., 4140 and 4340) as well as for high alloys (e.g., AerMet 100 and Maraging steels). Table 1 provides the three conditions that must be satisfied simultaneously for HE cracking to occur.

Table 1 Three conditions for hydrogen embrittlement cracking in carbon and low alloy steels

<table>
<thead>
<tr>
<th>(a)</th>
<th>Material’s susceptibility to HE cracking higher than a threshold level (S\text{Th}).</th>
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<td></td>
<td>Consensus is that the higher the strength or hardness, the higher the S\text{Th} (or the lower the σ\text{Th}). Carbon and low alloy steels with hardness higher than 34 – 35 HRC may be susceptible to EHE cracking especially when hot dip galvanized. Toughness is one of several metallurgical factors that could affect S\text{Th}. No correlation between S\text{Th} and CVN toughness has been established. That is, high strength steels with CVN toughness of 40 ft-lbs at 40ºF could still fail due to EHE. Caltrans has been over-emphasizing the role of toughness in the EHE failures of S1 and S2 anchor rods in March 2013.</td>
</tr>
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<table>
<thead>
<tr>
<th>(b)</th>
<th>Hydrogen concentrations higher than a threshold level (H\text{Th}).</th>
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<tr>
<td></td>
<td>H\text{Th} could range from 0.1 ppm to 1 to 2 ppm or higher depending on S\text{Th}, σ\text{Th}, and alloy compositions. Environmental hydrogen embrittlement (EHE) failures would take time from months to years because it takes time for the steel to absorb and build up hydrogen concentrations to H\text{Th} or higher, as affected by environmental conditions and rod surface conditions. Steel can absorb hydrogen with or without being stressed.</td>
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<table>
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<th>(c)</th>
<th>Sustained tensile stress higher than a threshold level (σ\text{Th}).</th>
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<td></td>
<td>σ\text{Th} could vary also depending on (a) and (b) above. Most threaded fasteners, including HDG BD rods, are under sustained tensile stresses after having been pretensioned (or preloaded). When pretensioned by nut engagements, stress concentration effects would raise the stresses at the roots of rod threads engaged by the nuts to higher than the target pretension stress level. It would be incorrect to state, strictly speaking, that the HDG BD rods in the SAS are “safe” from EHE failures because they were pretensioned to 0.70Fu and their EHE threshold stress is 0.75Fu. Caltrans EHE test data do not support 0.75Fu as an EHE threshold stress for all the HDG BD rods in the SAS.</td>
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Unlike tensile properties or hardness, each of the above three factors is difficult to determine precisely because they are interrelated to each other. To determine σ\text{Th} (or σ\text{EHE}) for example, the specimens must

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12 Private communications from Prof. Pense, July 15, 2013, and from Prof. McMahon, November 12, 2014.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

contain hydrogen concentrations higher than \( H_{th} \). The minimum stress that may cause HE cracking may continue to decrease with increasing hydrogen concentration above \( H_{th} \). Caltrans’ EHE test protocols required no hydrogen analysis. Caltrans has not explained why more than 60% of the EHE test specimens did not develop EHE cracks (e.g., intergranular cracks or IGC) when they were expected to. This is unscientific particularly because Caltrans’ EHE test protocols are “unprecedented;” they had never been proven to be valid previously. Caltrans should explain why the EHE threshold tests that did not develop EHE cracks during the loading cycles are scientifically acceptable, even to demonstrate credibility.

Table 2 compares the tensile and hardness requirements for several high strength structural steel fasteners.

<table>
<thead>
<tr>
<th>ASTM Standards/Grades</th>
<th>Tensile Strength ksi</th>
<th>Yield Strength ksi</th>
<th>Elong. %</th>
<th>Red.of Area %</th>
<th>Hardness, HRC</th>
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<tr>
<td>ASTM A490(^*)</td>
<td></td>
<td></td>
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<tr>
<td>½ - 1½ inches</td>
<td>150 min</td>
<td>170 max</td>
<td>130 min</td>
<td>14 min</td>
<td>40 min</td>
</tr>
<tr>
<td>Grade BD &gt;2 ½ - 4 inches</td>
<td>115 min</td>
<td>140 min</td>
<td>99 min</td>
<td>16 min</td>
<td>45 min</td>
</tr>
<tr>
<td>Grade BC &gt;2 ½ - 4 inches</td>
<td>140 min</td>
<td>115 min</td>
<td>115 min</td>
<td>14 min</td>
<td>40 min</td>
</tr>
<tr>
<td>ASTM F1554 Grade 105(^*)</td>
<td>125 min</td>
<td>150 max</td>
<td>105 min</td>
<td>15 min</td>
<td>45 min</td>
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<td>¼ - 3 inches</td>
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<td>½ - 1 inch incl.</td>
<td>120 min</td>
<td>105 min</td>
<td>92 min</td>
<td>81 min</td>
<td>25 - 34</td>
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<tr>
<td>1½ - 1½ inch incl.</td>
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<tr>
<td>ASTM A325(^*)</td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

ASTM A490 and A354 Grade BD each has a warning statement about the danger of HE cracking when structural bolts are hot dip galvanized (HDG), as follows.

**A490:**


**A354:**

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

Similar warning statements that HDG would increase the susceptibility of high strength steel to HE cracking may be found elsewhere, for example in ASTM A143, ASTM F2329, and FHWA-SA-91-031.\(^\text{17}\) Caltrans Bridge Design Specifications also gives the following warning about the HE cracking problems with Grade BD rods.\(^\text{10}\)

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\(^{14}\) ASTM A490 Standard Specification for Heat-Treated Steel Structural Bolts, 150 ksi Minimum Tensile Strength.

\(^{15}\) ASTM F1554 Standard Specification for Anchor Bolts, Steel, 36, 55, and 105-ksi Yield Strength.


\(^{17}\) ASTM A143 Standard Practice for Safeguarding Against Embrittlement of Hot dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement.


Thus, any engineers, civil or materials, who are using ASTM specifications on high strength threaded fasteners must be aware of the danger of HE cracking and should know the need for “a careful evaluation” before specifying HDG BD rods, particularly for large sizes weighing as much as 1,000 pounds each.

In spite of the above warnings about the HE failures of HDG BD rods, the Engineer of Record for the SAS span picked HDG BD rods for critical and non-critical applications in the SAS. Caltrans accepted the HDG BD selection without “a careful evaluation.”

Caltrans engineers were concerned only about internal hydrogen embrittlement (IHE) but were apparently unaware of environmental hydrogen embrittlement (EHE), which Caltrans often refers to as stress corrosion cracking (SCC). To avoid HE failures, Caltrans stipulated abrasive blast cleaning in lieu of acid cleaning of BD rods in preparation of HDG. IHE may be avoided by using abrasive cleaning. It would, however, have no effects on EHE. The 32 HDG BD rods for S1 and S2 failed, all in the bottom threads, because of EHE.

If the Engineer of Record, Caltrans, or both had done “a careful evaluation,” they would have imposed a maximum hardness limit on the HDG BD rods, in addition to the abrasive cleaning, if the use of Grade BD for its high strength was essential. A lower strength grade than BD, e.g., Grade BC, could have been used even for S1 and S2 anchor rods without much difficulties. Grade BC with a hardness requirement of 22 – 33 HRC for sizes over 2½ inches in diameter is not susceptible to HE failures with or without HDG.

“A careful evaluation” is needed particularly for large diameter HDG BD rods. The larger the diameter, the more “problems” need to be addressed in connection with hardenability of alloys such as the 4140 steel. The inclusion of 4340 steel specimens as part of the EHE test program is an indication that Caltrans has belatedly recognized the hardenability problems with the 4140 steel for large diameter HDG BD rods.

The 96 HDG BD anchor rods for S1 and S2 shear keys were exposed to pools of standing water in grout pipes for five years (because of construction delays) in the Pier E2 cap beam before they were pretensioned to 0.70Fu in March 2013. Caltrans and its contractors were unaware of the fact that hydrogen could be produced while the zinc coating, the steel, or both were corroding in the pools of water (or wetted by diurnal condensate film), could enter the rods while under no stress, increasing the hydrogen concentrations to higher than $H_{th}$, and could cause EHE failures when the rods were pretensioned to higher than $\sigma_{th}$. Some engineers, including Caltrans’ engineers/consultants, still think that the BD rods can absorb hydrogen only while being stressed or under stress. Hydrogen can enter the steel with or without being stressed, (just as hydrogen absorption can take place during electroplating), ready to start HE crack initiation/growth under a sustained tensile stress after pretensioning. This is how IHE failures occur. “Stress is not necessary during hydrogen uptake.”

Caltrans believes that 32 HDG BD rods for S1 and S2 failed due to EHE because these rods “[had] higher than normal susceptibility to hydrogen embrittlement.” Caltrans stated, “A comprehensive study of the

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mechanical and chemical properties of the rods conducted after the Townsend Test indicates that the greater susceptibility to hydrogen embrittlement of the 2008 rods is correlated with lower toughness.”

Caltrans has provided no definitive data to support the relationship between high HE susceptibility and low CVN toughness except that the failed HDG BD rods (produced in 2008) for S1 and S2 shear keys had lower CVN values than those produced in 2010. As will be shown later, Caltrans own test data show no differences in CVN values between the failed rods and the unfailed rods of S1 and S2 shear keys. Also, the PWS saddle tie rods, which were part of the 2010 production, have CVN values almost as low as those of “the 2008 rods.” If the 2010 HDG BD with higher CVN values than the 2008 HDG BD rods had been exposed to standing water for five years and pretensioned to 0.7Fu, it is highly probable some of them would have failed due to EHE cracking just as some of the 2008 rods did.

CVN toughness values can affect the susceptibility of HDG BD rods to HE cracking just as several other metallurgical factors do. However, there have been no systematic metallurgical studies that proved conclusively that the CVN toughness values can play a deciding role in EHE failures, on the par with strength or hardness. Consensus so far is that the strength (or hardness) of the material is a better measure of HE susceptibility than other metallurgical factors including CVN toughness. This is why most HE susceptibility data are plotted against strength or hardness. “Lower hardness greatly improves the inherent resistance to IHE/EHE and this is a major reason for the benefit of lower hardness.” No one has yet plotted HE susceptibility of a high strength fastener grade against CVN toughness values (because CVN toughness cannot be dissociated from other factors.) CVN toughness can affect the material’s susceptibility to HE cracking. Caltrans has been, however, overly emphasizing the role of CVN toughness in HE cracking based only on limited data. CVN toughness is affected by variations in alloy compositions and by such phenomenon as temper embrittlement (TE). This is another metallurgical subject as complex as HE. Caltrans has not taken TE into consideration when simply emphasizing the role of CVN values in EHE failures of the S1 and S2 rods.

HE failures may be prevented best by not using the material that is susceptible to HE cracking. It can be prevented in theory also by keeping the H concentration to below H\text{th} or by keeping the sustained tensile stress in the rods to below \sigma_{\text{th}}. In practice, however, these two options are difficult to consistently control successfully, because many factors can influence the outcome. This is why the pretension stress control has seldom been relied upon as a means of avoiding EHE failures of high strength steel fasteners that require a high pretension level (> 0.3 – 0.8Fu) in the construction industry.

The best option to resolve the HE failure problems is not to use material that is susceptible to EHE failures during service. This can be done by a simple hardness control, but that had to have been stipulated in the design stage, for example in a technical specification for the HDG BD rods for the SAS. The Engineer of Record for the SAS neglected to do this.

Grade BD allows a hardness range of 31 – 39 HRC (Table 2). Since A325 bolts with hardness up to 34 HRC, with or without HDG, are considered resistant to IHE/EHE failures (based on experience), not all HDG BD rods will fail due to EHE. That is, the HDG BD rods with hardness lower than 34 - 35 HRC (anywhere across the rod cross section) would be unlikely to fail due to EHE. Some of the 32 HDG BD rods for S1 and S2 that failed had 36 HRC near the surface. If Caltrans had imposed a maximum surface hardness requirement for HDG BD rods, such as 34 or 35 HRC maximum for each threaded end, and verified this requirement was complied with, no shear key anchor rods would have failed due to EHE and there would be no concerns about potential EHE failures of any of the HDG BD rods in the SAS span. Therefore, the Engineer of Record is most responsible for the costly EHE problems in the SAS.

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19 Reference 8, p. ES-3. The 2008 rods refer to the 3 inch diameter HDG BD rods produced in 2008 for S1 and S2 shear keys.
20 Private Communication from R. Kane, November 19, 2014.
The mere lack of a maximum hardness requirement has cost Caltrans $25 million for the S1 and S2 anchor rod “retrofit” and additional $20 million for a test program that Caltrans calls “unprecedented.” Contrary to what Caltrans wants the public to believe, the EHE failure problems remain unresolved after the $20 million test program. It was a poor test program that was hatched under ill-conceived premises: (1) there was nothing wrong with the HDG BD selection for the SAS to begin with, (2) EHE failures can be “prevented” by proving that the EHE threshold stresses are higher than the pretension levels, and (3) the 32 HDG BD failures were due to their low CVN toughness, a more-or-less rare occurrence that is unlikely to exist in the remaining HDG BD rods in the SAS. These premises are all incorrect.

3.0 CALTRANS’ HDG BD ROD TESTS FOR HYDROGEN EMBRITTLEMENT PREVENTION

In the case of the SAS span, the 2,306 HDG BD rods were installed without first checking the hardness of individual HDG BD rods. One of the options for Caltrans to resolve the concerns about the potential future EHE failures of the HDG BD rods in the SAS span has been to identify and replace the ones that may be susceptible to HE cracking. This option is applicable to all HDG BD rods in the SAS span except for the tower base anchor rods, which are not replaceable. This approach could have been cost effective as compared with the $20 million test program. A separate plan would be necessary for the tower anchor rods. Some of them could eventually fail due to EHE as will be discussed later: maybe not now, but some time during the long (150) years of service, which is double the usual 75 year design life for most bridges in the US.

Caltrans has never considered the merits of identifying and replacing the HDG BD rods that may be susceptible to HE cracking because of high hardness and not because of low CVN values at 40 °F. Instead, Caltrans embarked on a testing program, including the unproven and expensive EHE (Townsend) test protocols, using full size HDG BD anchor rods, ranging up to 4 inches in diameter, as test specimens. Although Caltrans claims this test program is “unprecedented,” both technically and financially, it was unfortunate that Caltrans lacked the technical expertise that is required to carry out the “unprecedented” materials engineering test program, scientifically. This is apparent because of numerous technically questionable statements and conclusions in reports and technical presentations that have been produced or released by Caltrans on the HDG BD rods in the SAS since the shear key anchor rod failures, including the most recent one, the draft report on the A354 BD Evaluation. Caltrans simply lacks the expertise and experience to design and conduct one of the most complicated materials property testing programs: EHE threshold stress determination using unproven test protocols.

After a year and half of various tests (Tests I – VI), spending $20 million, Caltrans released the following draft report:

| SAN FRANCISCO-OAKLAND BAY BRIDGE |
| SELF-ANCHORED SUSPENSION BRIDGE |
| EVALUATION OF THE ASTM A354 GRADE BD RODS | September 30, 2014 |

In this draft report, Caltrans concluded that the 32 HDG BD rods for S1 and S2 failed in March 2013 because they were exceptionally high in susceptibility (due to low CVN values according to Caltrans) to HE cracking and the rest (2,210 HDG BD rods) are acceptable for service because their EHE threshold loads are 0.75- 0.85Fu, which are higher than their pretension level: 0.10 – 0.70Fu.

Unfortunately, this conclusion is based on erroneous test data interpretations and on neglecting the non-uniform stress distributions in any threaded rods that are pretensioned by nuts, particularly in large rods as long as 26 ft or 32 ft. Caltrans’ EHE test protocols and the reasons for picking the 0.75 – 0.85Fu as the EHE threshold stresses for the 2,210 HDG BD rods are unscientific and unsupported by the test data generated by Tests I - VI.
3.1 Tests I – VI, Caltrans’ Grade BD Anchor Rod EHE Failure Prevention Program

Caltrans could have identified the HDG BD rods that may be susceptible to EHE cracking and replaced them with new ones not susceptible to EHE cracking based on hardness tests. (It will be shown later that the hardness data that Caltrans produced are unreliable and may not be used for this purpose without doing more (accurate) in-situ field hardness tests.)

Instead, Caltrans and its contractors wanted to “prove” that the EHE threshold stress is higher than the pretension level (0.10 – 0.70Fu) for all of the HDG BD rods in the SAS span. As mentioned before, however, this entire scheme was hatched with lack of understanding of three key factors in HE cracking in threaded connections, as follow.

(a) EHE threshold stresses are related to $S_{th}$, which can be correlated to hardness/strength.

(b) Local conditions, not average material properties, such as locally high stresses or locally high hydrogen concentrations determine whether or not HE cracks can initiate, grow, or both.\textsuperscript{21}

(c) Stress concentration effects at rod thread roots when pretensioned by nut engagements would increase the stresses at local regions, such as at the roots of the rod threads engaged by nuts, to several times higher than the target (global) pretension level used, such as 0.32Fu or 0.45Fu.\textsuperscript{22}

Neglecting the three most important factors in HE cracking of threaded connections, above, Caltrans and its contractors devised and carried out a large-scale test program in Table 3.\textsuperscript{23}

<table>
<thead>
<tr>
<th>Table 3 Caltrans post S1 and S2 anchor rod EHE failure test program</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Commentary in pink boxes added)</td>
</tr>
</tbody>
</table>

The objective of the above test program was to devise a strategy that can prevent all the HDG BD rods in the SAS span from EHE failures. Instead, they ended up “proving” that they are “safe as designed and as installed” from EHE failures during the 150 year SAS design life and that only supplementary protections

\textsuperscript{23} Ref. 8, p.16.
such as “grease cans and painting” are necessary. Tests I – IV have been essentially complete. Tests V – VI are in the final phase as of September 30, 2014.

Based on the data from Tests I - VI, Caltrans, along with the Engineer of Record, declared, 24,25

> Based on the above it is concluded that the A354BD rods in service on the SAS are safe as they are not susceptible to SCC at the design loads and conditions.

As will be shown later, however, this conclusion is not supported by the Test I – VI data. Caltrans has missed various factors that should have been taken into consideration in devising the EHE test protocols and interpreting the test data. As a result, Caltrans has resolved nothing regarding possible EHE failures of critical anchor rods in the SAS shown in Figure 2.

### 3.2 Caltrans’ S1 and S2 Rod Specimens

Caltrans gave the following list of 14 rods, extracted from Group 1 (the 2008 rods), and Figure 3. 26

<table>
<thead>
<tr>
<th>Rod ID</th>
<th>Failed</th>
<th>Rod ID</th>
<th>Failed</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1A1</td>
<td>Yes</td>
<td>S2B2</td>
<td>No</td>
</tr>
<tr>
<td>S1A2</td>
<td>Yes</td>
<td>S2B4</td>
<td>yes</td>
</tr>
<tr>
<td>S1B3</td>
<td>Yes</td>
<td>S2G8</td>
<td>No</td>
</tr>
<tr>
<td>S1G6</td>
<td>No</td>
<td>S2H3</td>
<td>yes</td>
</tr>
<tr>
<td>S1G7</td>
<td>Yes</td>
<td>S2H4</td>
<td>yes</td>
</tr>
<tr>
<td>S1H1</td>
<td>Yes</td>
<td>S2H5</td>
<td>No</td>
</tr>
<tr>
<td>S1H2</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1H7</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Actually, which rods Caltrans extracted from S1 and S2 and what tests were done to them are not straightforward. For example, Caltrans did not list S1H3 in the above table. It was, however, one of the failed rods of S1 that was removed on May 15, 2013 26 and extensively tested, including CVN toughness. Therefore, it was included in Figure 3. Caltrans extracted 10 S1 rods and 8 S2 rods, including 5 from unfailed rods, which Reference 8 does not state, indicate, or discuss.

### 3.3 Test I and II - Hardness and Other Lab Tests

Using MIC 10 (Figure 4), Caltrans had in-situ hardness tests done across the cross sections of over 1,000 HDG BD rods that had been installed in the SAS span. 27 The results are presented in File E17, which also includes the data from laboratory HRC and HK (Knoop microhardness) tests, tensile tests (using both machined specimens and full size rods), Charpy V-notch (CVN) toughness tests, and chemical composition tests. 28

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24 The “Engineer on Record” is T. Y. Lin International and Moffat & Nichols, Joint Venture.
26 Ref. 8, p. 2-5 and 2-18.
28 E.17 - SAS A354BD Testing Program Results Tests 1, II and III
Additional MIC-10 and lab HRC tests were done for specimens of Groups 2 – 18 (Table 5 and Appendix A2). Reference 8 presented, however, only average HRC data, which are not useful in evaluating the potentials for EHE failures. As mentioned before, for HE evaluation, the highest hardness would be of interest rather than average hardness.

Although the lab tests included Knoop microhardness (HK) tests, no hardness or hardness gradient data have been presented for the roots of the cold rolled threads of HDG BD rods. File E17 contains a mass of hardness data. Many of them need to be evaluated, re-tested, or both because they do not make sense metallurgically as will be discussed later.

Figure 5 presents CVN energy absorption data for S1 and S2 rods (the “2008 rods”), including four rods that did not fail in March 2013. The CVN specimens were obtained in the axial direction, close to circumferential surface with the notch perpendicular to the axis.

Figure 5 shows no distinction in CVN values between the failed and the unfailed rods of the S1 and S2 (or the “2008 rods”). The CVN data obtained from the center of the “2008 rods” were slightly lower in ft-lbs values (14 – 16 vs 10 – 12 ft-lbs at 40º and 70ºF, respectively.) They, too, showed no distinction in CVN values between the failed and the unfailed rods. Therefore, the CVN toughness cannot be used as the main reason why some failed while the others did not. Caltrans needs to explain why the 64 rods did not fail using other data than CVN values.

Figure 6 compares CVN toughness data of the “2008 rods” with those of other groups. Although the “2006 and 2010” rods display higher CVN values than the “2008” rods, two of the “2010” rods (Groups 7 and 8) are not much different from the “2008” rods.

These variations are commonly observed from one heat of steel to another as influenced by various manufacturing variables, including not only heat treatment but also tramp elements, such as oxygen (O), nitrogen (N), phosphorus (P), sulfur (S), antimony (Sb), tin (Sn), arsenic (As), copper (Cu), etc. Caltrans’ chemical analyses of various rod specimens did not even include several of these elements. Because many variables affect CVN values, they show a notoriously wide scatter in data. The above scatter in data by Caltrans is only a tip of an iceberg.

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29 Ref. 8, p. 2-15 – 16.
30 Ref. 8, p. 2-23, 2-17.
These CVN data would indicate that the CVN toughness was not an important factor in the failures of S1 and S2 rods on Pier E2 in March 2013 as Caltrans tries to make it out to be. Unless Caltrans can explain why only the 32 rods failed and the 64 rods did not fail, they may not play up the role of CVN toughness in HE cracking in order to separate the 96 of the “2008 rods” as poor quality steel from the rest of the 2,210 rods. As mentioned before, Caltrans does not have enough data to back up their assertion about the effects of CVN toughness on IHE/EHE failures.

No correlation between CVN toughness and EHE susceptibility has been established in the literature. The higher the CVN values, however, the larger the critical crack size \(a_c\) that a rod can sustain before the onset of the final fast fracture. Therefore, in theory, the higher the CVN values, the longer the time a rod can sustain the given stress. It will, however, eventually fail if \(S_{th}\), \(H_{th}\), and \(\sigma_{th}\) have been satisfied. Therefore, the benefit of high CVN values is not great.

### 3.4 Test III – Tensile Properties

Caltrans presented the Test III data in ksi rather than in kips (Figure 7). Caltrans did not label the abscissa of Figure 7.

These data showed a median of about 158 ksi, which is about 1.13\(F_u\), where \(F_u\) is 140 ksi for HDG BD rods for sizes greater than 2½ inches.

The tensile strength data from machined specimens, taken at mid-radius in Test II, were comparable to the full size test data in Figure 7.

The tensile property data in Reference 8 indicate that the tensile strengths ranged between 156 and 170 ksi for Group 1 (the 2008 rods) and between 156 and 163 ksi for Groups 2 – 12 (the 2006 and 2010 rods) as shown in Table 4, below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tensile Strength (psi)</th>
<th>Yield Strength (psi)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM Req.</td>
<td>YS/TS</td>
<td>Min. 140000 (except Group 4 Min 150000)</td>
<td>Min. 115000</td>
</tr>
<tr>
<td>Group 2</td>
<td>Sample 1</td>
<td>160000</td>
<td>140000</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Sample 2</td>
<td>157000</td>
<td>138000</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Sample 3</td>
<td>157000</td>
<td>139000</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>Sample 4</td>
<td>160200</td>
<td>141000</td>
<td>0.89</td>
</tr>
<tr>
<td>Group 3</td>
<td>Sample 1</td>
<td>156300</td>
<td>140900</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>Sample 2</td>
<td>157600</td>
<td>138900</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Sample 3</td>
<td>156400</td>
<td>137800</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Sample 4</td>
<td>159100</td>
<td>141200</td>
<td>0.87</td>
</tr>
<tr>
<td>Group 4</td>
<td>Sample 1</td>
<td>159900</td>
<td>146700</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Sample 2</td>
<td>156600</td>
<td>144400</td>
<td>0.92</td>
</tr>
<tr>
<td>Group 7</td>
<td>Sample 1</td>
<td>158300</td>
<td>138800</td>
<td>0.88</td>
</tr>
<tr>
<td>Group 8</td>
<td>Sample 1</td>
<td>161500</td>
<td>136400</td>
<td>0.84</td>
</tr>
<tr>
<td>Group 12</td>
<td>Sample 1</td>
<td>163300</td>
<td>147600</td>
<td>0.91</td>
</tr>
</tbody>
</table>
3.5 Tests IV – VI Stress Corrosion (Environmental Hydrogen Embrittlement) Cracking Tests

3.5.1 Test IV – Townsend Test to Determine EHE Threshold Stresses for HDG BD Rods in the SAS

The Test IV (the Townsend test) set-up is illustrated in Figure 8.

Caltrans built as many as 17 Townsend test rigs, each on a concrete pad. Each of the two threaded ends is encased in a 3.5% NaCl aqueous solution chamber at room temperature to facilitate the corrosion of the zinc coating, the steel, or both. The specimens are incrementally loaded from 0.30 to 0.80Fu, holding for 48 hours at each step, before increasing the load to the next higher step. The specimens are held for 140 hours (5.8 days) at 0.85Fu as the last incremental step. The total time in the saltwater chambers was 572 hours (~24 days).

Afterwards, if not failed in 572 hours, the load was increased monotonically until the specimens failed regardless of whether EHE cracks (e.g., intergranular cracks or IGC) had developed or not. The results are presented in Table 5 (next page) and Figure 9 (page 16).

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31 Caltrans used the term stress corrosion or stress corrosion cracking (SCC) in Ref. 8. SCC has been changed to EHE in this review. IHE does not involve corrosion; it should not be included as part of SCC.

### Table 5 The Results of Test IV
(Column numbers and Notes 8 – 14 added in this review)

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Group ID</th>
<th>Rod No.</th>
<th>Max Load %Fu</th>
<th>Field Max Hardness HRC @ 1/4&quot; from O.D. (1)</th>
<th>Lab Average Hardness HRC at Root (200)</th>
<th>Impact Toughness CVN ft-lbs @ 40F</th>
<th>Potential at F/N At Load Volts vs Saturated Calomel Electrode (400)</th>
<th>Intergranular Cracking Detected in SEM?</th>
<th>EHE Threshold % Fu (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D1</td>
<td>2</td>
<td>85</td>
<td>JE 37</td>
<td>37</td>
<td>-0.92</td>
<td>Yes (8)</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>D1</td>
<td>2</td>
<td>80</td>
<td>JE 36</td>
<td>36</td>
<td>-0.92</td>
<td>Yes (7)</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S3</td>
<td>2</td>
<td>111</td>
<td>DE 39</td>
<td>39</td>
<td>-0.90</td>
<td>No</td>
<td>85 (9)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>S4</td>
<td>2</td>
<td>85</td>
<td>DE 35</td>
<td>36</td>
<td>-0.93</td>
<td>Yes</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Spire</td>
<td>4</td>
<td>2.9o</td>
<td>5Rolled 101</td>
<td>34</td>
<td>40 (13)</td>
<td>29</td>
<td>-0.88</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>T1 Base</td>
<td>1</td>
<td>6</td>
<td>117</td>
<td>35</td>
<td>38</td>
<td>39</td>
<td>-0.87</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>T1 Top</td>
<td>1</td>
<td>8.4o</td>
<td>7Rolled 11</td>
<td>34</td>
<td>36</td>
<td>36</td>
<td>-0.95</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>PWS 7.85o</td>
<td>6</td>
<td>10</td>
<td>110</td>
<td>33 38 (14)</td>
<td>39</td>
<td>39</td>
<td>Yes (10)</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>PWS 7.85o</td>
<td>10</td>
<td>10</td>
<td>36</td>
<td>36 36</td>
<td>36</td>
<td>-1.01</td>
<td>No</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>4540</td>
<td>18</td>
<td>HDG</td>
<td>109</td>
<td>35</td>
<td>N/A</td>
<td>-0.96</td>
<td>No (8)</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>4540</td>
<td>18</td>
<td>HDG</td>
<td>110</td>
<td>36</td>
<td>N/A</td>
<td>-0.94</td>
<td>No (8)</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>4540</td>
<td>18</td>
<td>Black</td>
<td>113</td>
<td>48</td>
<td>N/A</td>
<td>-0.70</td>
<td>No (8)</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>4540</td>
<td>18</td>
<td>Black</td>
<td>113</td>
<td>48</td>
<td>N/A</td>
<td>-0.70</td>
<td>No (8)</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>51A7</td>
<td>18</td>
<td>HDG</td>
<td>115</td>
<td>36.5</td>
<td>N/A</td>
<td>Dry Test</td>
<td>No (12)</td>
<td>85</td>
</tr>
<tr>
<td>2</td>
<td>51A8</td>
<td>19</td>
<td>HDG</td>
<td>115</td>
<td>35.5</td>
<td>N/A</td>
<td>Dry Test</td>
<td>No (12)</td>
<td>85</td>
</tr>
</tbody>
</table>

**Notes:**

6. In accordance with normal practice (e.g., ASTM F1681), the threshold values given in Table 3.1-3 represent the last load step at which cracking was not detected.

7. N/A indicates data not yet available to date.

8. Only 7 out of 19 specimens fractured with intergranular cracks (IGC).

9. 0.85Fu as the EHE threshold load is too arbitrary to be acceptable. No EHE cracks developed.

10. If cracking was detected at 0.85Fu, how did these two specimens reach 1.1 – 1.2Fu at failure?

11. With hardness at 34 – 35 HRC, this specimen should not have developed EHE failures.

12. What were the hydrogen contents?

13. No EHE cracks and 40 HRC contradict each other. Also, the two hardness numbers, 34 HRC and 40 HRC, of the same rod do not make sense. Either one or both could be wrong.

14. Either one or both of the hardness numbers could be wrong or Caltrans needs to explain why the hardness numbers in HRC vary as much as 4 to 6 points for the same specimens (or rods).

Note 6 of Table 5 by Caltrans about EHE threshold stress (Column 10) is as follows:

6. In accordance with normal practice (e.g., ASTM F1681), the threshold values given in Table 3.1-3 (or Table 5 above) represent the last load step at which cracking was not detected.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

Note 6 cannot be, however, applicable to the specimens that showed no signs of EHE cracks (or IGC), for example to Rod #3. According to Column 6, Rod #3 has 39 HRC at a thread root, higher than the HRC of Rods #1, 2, and 4. But, it is Rod #3 that did not fail due to EHE. It is a mystery why #3 did not develop EHE cracking as did #1, 2, and 4 with HRC hardness lower than that of #3. This should have alerted Caltrans and its contractors during Phase 1 that there could be something amiss in the Test IV protocols.

What Caltrans needed to do was to find out why Rod #3 did not develop EHE cracks during Phase I. Instead of finding out possible reasons in the test protocols that may be responsible for the no EHE cracks in spite of the high hardness and correcting them, Caltrans interpreted without scientific basis that no EHE cracks is equivalent to an EHE threshold stress of 0.85Fu and marched on through to Rod #19. Rod #3 should have been considered a “no test.” Several reasons why it should be a “no test” will be discussed later.

Caltrans used only the dead end saltwater chamber for some short rod specimens, probably using a long coupler to the hydraulic jacks at the loading end. Caltrans did not indicate which rod specimens were tested with only one saltwater chamber. Neither did they indicate the failure locations in Table 5. These are important data that are missing from Reference 8. The failure locations are mentioned only for Rods #1 – 4 as indicated in Table 5.

In Table 5, only 7 specimens out of 19 are indicated to have intergranular cracks (IGC), “detected by SEM” (scanning electron microscopic examination) of the fracture faces after the tests. The remaining 12 specimens had no signs of IGC or other types of crack initiations or growth under sustained stress cycles. Thus, these specimens, for example, Rod #3, could not have an EHE threshold stress as indicated by Note 9. It is simply that an EHE threshold stress cannot be defined for the specimens that did not develop EHE cracks, either in IGC or non-IGC. (Not all HE cracks are IGC.)

On the other hand, the specimens (e.g., #3 – see below) that did not develop EHE cracks in Test IV may not be immune to EHE failures during service, judging from its hardness, 39 HRC. So, the 12 specimens that had no EHE cracks should have been considered “no tests.” Rod #8 with 32 – 35HRC may be immune to EHE failures; however, one may not arbitrarily assign an EHE threshold stress of 0.85Fu to it. Conversely, Rod #3 with 36 – 39 HRC (see below) may fail due to EHE during service and may have an EHE threshold stress lower than 0.85Fu. Therefore, 0.85Fu as an EHE threshold stress for the 12 specimens that did not develop EHE cracks is invalid.

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Group ID</th>
<th>Rod No.</th>
<th>Max Load %Fu</th>
<th>Field Max Hardness HRC @ 1/4&quot; from O.D.</th>
<th>Lab Average Hardness HRC at Root</th>
<th>Impact Toughness CVN ft-lbs @ 40F</th>
<th>Potential at FIN/Al Load Volts vs Saturated Calomel Electrode</th>
<th>Intergranular Cracking Detected in SEM?</th>
<th>EHE Threshold %Fu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1</td>
<td>1</td>
<td>85</td>
<td>37</td>
<td>37</td>
<td>-0.92</td>
<td>Yes (8)</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>1</td>
<td>B1</td>
<td>2</td>
<td>80</td>
<td>36</td>
<td>37</td>
<td>-0.92</td>
<td>Yes</td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>1</td>
<td>S3</td>
<td>2</td>
<td>111</td>
<td>36</td>
<td>39</td>
<td>-0.90</td>
<td>No</td>
<td></td>
<td>85 (9)</td>
</tr>
<tr>
<td>1</td>
<td>S4</td>
<td>2</td>
<td>85</td>
<td>35</td>
<td>36</td>
<td>-0.93</td>
<td>Yes</td>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>

Caltrans plotted the data in columns 5 and 10 in Table 5 in Figure 9 (next page). It will be shown later that Figure 9 involves many data points that were plotted at wrong places and used wrong identification numbers. One example each is indicated below.

Ref. 8, p. 3-1.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

In the above figure, Caltrans drew a straight horizontal line at 0.75Fu as the EHE threshold stress for all HDG BD rods in the SAS span, across a hardness range of 30 - 42 HRC. This is erroneous in principle and unscientific. (This is the same mistake in nature as that of Figure 34 of the July 2013 TBPOC report.) The straight horizontal line at 0.75Fu does not conform to the general HE cracking behavior that the HE (for both IHE and EHE) threshold stress (or threshold stress intensity factors) would decrease with increasing hardness. Also, for the region between 30 – 34 HRC, a threshold stress may be undefined because the specimens in this hardness range could be immune or resistant to HE cracking. Also, an HDG BG rod with 42 HRC would have a much lower EHE threshold stress than 0.75Fu (or 105 ksi).

The 0.75Fu horizontal line may be labeled as the lowest EHE threshold stress for all the BD rods in the SAS span, but not all the way down to 30 HRC or all the way up to 42 HRC. Caltrans has neither done the necessary tests nor do they have the data to support 0.75 Fu as the lowest EHE threshold stress. To determine the lowest EHE threshold stress, Caltrans needs to know the highest hardness that exists in the HDG BD rods in the SAS, for example 43 HRC. Apparently, Caltrans does not understand why this is important. The massive amount of hardness tests was conducted without a specific purpose or proper evaluation. The hardness data in Table 5 as well as those in File E17 are untrustworthy as mentioned before. The reasons why they are untrustworthy will be discussed later.

Reference 8, Figure 3.1-10: Test IV Failure Loads for A354BD Rods, p.3-13, or Figure 4.3-1: Test IV Failure Loads for A354BD Rods, p. 4-4
The Test IV protocols were patterned after ASTM E1681 for determining $K_{\text{EAC}}$ or $K_{\text{IEAC}}$.$^{35}$ The former attempts to determine EHE threshold stresses using actual HDG BD rods, 2 to 4 inches in diameter, as specimens without precracks and by measuring the load or stress at which EHE cracks initiate. The latter is for determining EHE threshold stress intensity factors ($K_{\text{EAC}}$ or $K_{\text{IEAC}}$) by using specimens with precracks and by measuring the maximum load at which crack growth did not occur.

ASTM E1681 states, “When a material in a certain environment is not susceptible to environment-assisted cracking, it will not be possible to measure $K_{\text{EAC}}$ or $K_{\text{IEAC}}$.”$^{36}$ Likewise, it will not be possible to measure (or define) an EHE threshold stress for a specimen that did not develop EHE cracks (or IGC) during the Test IV loading cycle. Thus, the 0.85$F_u$ as EHE threshold stresses for the 12 specimens that did not develop EHE (or IGC) cracks during the 572 hour saltwater tests in Table 5 are invalid. Their plots in Figure 9 are meaningless for purposes of assuring high EHE threshold stresses for the HDG BD rods in the SAS. There are more specimens that resulted in “no tests” than valid results with EHE cracks (or IGC).

The highest hardness in Table 5 is 41 HRC for Rod #11. It did not develop EHE cracks (or IGC). File E17 has an HDG BD rod with 43 HRC (to be shown later).$^{28}$ Some of the 12 specimens that did not develop EHE cracks or some HDG BD rods with hardness as high as 43 HRC could have EHE threshold stresses lower than 0.75$F_u$ or lower than even 0.70$F_u$ (or 98 ksi). Thus, Caltrans may not rely only on the data in Table 5 to state that 0.75$F_u$ is the minimum EHE threshold stress for all the HDG BD rods in the SAS.

Another reason why the data in Table 5 are not useful is as follows. Rods #12, 13, 18, and 19 belong to the same group, Group 1 (Pier E2 “2008 rods” that failed). The two ■’s, marked #18 and #19 in Figure 9 should have been marked #1’s. Rods #12 and 13, which are marked #1’s in Figure 9, failed at 0.70$F_u$. Caltrans interpreted these results to mean an EHE threshold stress of 0.65$F_u$ because no EHE cracks occurred at 0.65$F_u$. When Rods #18 and 19 from the same Group 1 were step loaded in air, they did not show HE cracks; both reached 1.15$F_u$ (or 154 ksi) at failure. Caltrans interpreted these results to mean an IHE threshold stress of 0.85$F_u$ (or 119 ksi).

Again, this is an erroneous interpretation. No HE cracks, either due to IHE or EHE, in Rods #18 and 19 would mean that both are “no tests,” as discussed above. The most probable reason that #18 and 19 did not show IGC during the step loading cycles in air was that its H concentration was lower than $H_{\text{f}}$. No tests for hydrogen concentrations were done for #18 and 19 to see if it had satisfied $H_{\text{f}}$. So, Caltrans has no proof for 0.85$F_u$ as the IHE threshold stress for #18 and 19. Conceptually, one HDG BD rod cannot have one threshold stress value for IHE and another for EHE. Both IHE and EHE should have the same threshold stress if both satisfied $H_{\text{f}}$.

Rods #12, 13, 18 and 19 came from Group 1 (manufactured in 2008), the failed anchor rods for S1 and S2 that were branded as having “higher than normal susceptibility to HE cracking” because of low CVN toughness. These four specimens are comparable to each other in hardness. Their HE (both IHE and EHE) threshold stress should be about the same, whatever that may be, regardless whether the test was done in air or in saltwater, as long as $H_{\text{f}}$ was satisfied. It should not vary from 0.65$F_u$ to 0.85$F_u$, a 30% increase, depending on the test environments. This proves that the method of determining an EHE threshold stress according to Note 6 is arbitrary and erroneous. Thus, the data in Table 5 or Figure 9 are useless as a backup for the 0.75$F_u$ as the EHE threshold stress.

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35 ASTM E1681 Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials. $K_{\text{EAC}}$ is stress intensity factor for threshold for environment assisted cracking. It is the highest value of K at which crack growth is not observed for the particular test protocols (para 3.1.5). $K_{\text{IEAC}}$ is stress intensity factor threshold for plane strain environment-assisted cracking (para 3.1.4).

36 ibid, Para 5.1.6.
Had these specimens been held at 0.75Fu or 0.80Fu before the load was increased to failure, Caltrans would have interpreted the results to mean an EHE threshold stress of 0.75 or 0.80Fu, rather than 0.85Fu. Thus, the data interpretations of Test IV by Caltrans are unscientific and arbitrary. Rods #18 and #19 should have been classified as “no tests.” They only proved that they failed due to overload, not due to the HE cracking mechanism. Likewise, the other ten specimens that showed no EHE cracks should be treated as “no tests” rather than equating to an EHE threshold stress of 0.85Fu. Caltrans needs to determine the reasons why more than 60% of the tests produced no useful data. Caltrans should have done a hydrogen analysis as soon as a test was completed. This was not done, however.

Regardless of whatever groups or regardless of whether tested in 3.5%NaCl solution or in air, the EHE threshold stress should decrease with increasing hardness. The EHE threshold stress as a material property should not change from one set of test protocols to another. More discussions as to why the Test IV data are problematic are given in Section 4.0.

3.5.2 Tests V (Raymond Test) - Incremental Step Loading Test (ASTM F1624)

Raymond presented the objective of Test V, as follows.37

![Objective: Measure threshold stress intensity load for the onset of hydrogen induced stress cracking](http://baybridgeinfo.org/sites/default/files/pdf/6.%20Test%20V%20(Raymond)_v02.pdf)

Notice the term “threshold stress intensity load,” not “threshold stress load or threshold stress intensity factor.” These are inter-related, though not the same.

The Raymond test set-up is illustrated in Figure 10a. Specimens are similar to Charpy V-notch (CVN) toughness test specimen (10 x 10 x 55 mm or about 0.4 x 0.4 x 2.2 inches) as shown in Figures 10b and 10c. The tests were carried out in a 3.5% NaCl aqueous solution bath in accordance with ASTM F1624.38

![Type V test set-up](http://baybridgeinfo.org/sites/default/files/pdf/6.%20Test%20V%20(Raymond)_v02.pdf)

![Two types of specimens, CVN size](http://baybridgeinfo.org/sites/default/files/pdf/6.%20Test%20V%20(Raymond)_v02.pdf)

![A BD rod after removing specimens](http://baybridgeinfo.org/sites/default/files/pdf/6.%20Test%20V%20(Raymond)_v02.pdf)

Figure 10 Test V (Raymond Test) – CVN sized specimens removed from BD rods as shown in (b) and (c) are incrementally loaded in four point bending in 3.5% NaCl solution.

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37 Slide 7 http://baybridgeinfo.org/sites/default/files/pdf/6.%20Test%20V%20(Raymond)_v02.pdf
3.5.3 Test VI (Gorman Test) – Slow Strain Rate Test

Figure 11 shows the test set-up used for Test VI, the Gorman test, or a slow strain rate test.\(^{39}\)

Gorman gave the following motivation for Test VI: “Time dependent processes may reduce resistance of rods to hydrogen embrittlement/stress corrosion cracking (HE/SCC). For example, hydrogen concentration may increase with time [and] thread root geometry may change with time as a result of corrosion.” Test durations up to 5,000 hours (208 day) have been included in the test protocols, similar to those in ASTM E1681 and F519.\(^{40,41}\) Caltrans included a partial result of Test VI in the draft report.\(^{42}\)

4.0 EVALUATION OF CALTRANS TEST IV PROTOCOLS AND DATA

4.1 Caltrans’ EHE Threshold Stress Data – Inconsistent and Invalid

Based on the results of Tests I – VI, Caltrans claims the following EHE threshold stresses.\(^{43}\) All are based on erroneous interpretation of test data as discussed before and therefore, invalid. The first two sentences about the confidence of the test protocols being valid are also invalid as will be discussed later.

| Test IV duplicated the failures of 2008 rods on Pier E2 in terms of breaking loads and mechanism of failure. This provides confidence in the results obtained with these and the other rods, as follows. |
|:---|:---|:---|
| 1. The EHE threshold of the 2010 Pier E2 rods is 0.75 Fy. | 2. The EHE threshold of the 2008 Pier E2 rods is 0.65 Fy. | 3. The difference between the 2008 and 2010 Pier E2 thresholds can be attributed to differences in toughness and a higher iron content of the galvanized coating on the 2010 rods (the higher iron content reduces the electrochemical driving force for hydrogen deposition on the steel). |
| 4. EHE threshold of the various 2010 and 2006 rods varies from 0.80 Fy to 0.85 Fy. | 5. The EHE threshold of 3.5-inch PWS rods with threads rolled after heat treatment is 0.85 Fy, and is superior to that of similar rods with cut threads, with a threshold of 0.80 Fy. | 6. The EHE threshold of black 2013 Pier E2 rods is 0.85 Fy. |
| 7. The EHE threshold of galvanized 2013 Pier E2 rods is 0.85 Fy. | 8. The IHE threshold of 2008 rods is 0.85 Fy. |


\(^{42}\) Ref. 8, p.3-31.

\(^{43}\) Ref. 8, pp. 3-14, 4-3.
In essence, Caltrans is claiming that the HDG BD rods in the SAS are “safe” from future EHE failures because the Test IV data indicate their [EHE] threshold stresses are 0.75 – 0.85Fu, excluding the “2008 rods” for S1 and S2, and the rods are pretensioned to 0.70Fu or lower. As discussed below, however, none of the above eight claims can be validated.

For example, “2. The EHE threshold of the 2008 Pier E2 rods is 0.65Fu” cannot be true. If this were true, all of the 96 HDG BD rods for S1 and S2 should have failed because they were pretensioned to 0.70Fu. In reality, only 32 failed and 64 did not fail. Caltrans does not even know the hardness distribution of the 64 HDG BD rods that did not fail. If 0.65Fu as the EHE threshold stress were true, the remaining 64 HDG BD rods for S1 and S2 should have failed regardless of their CVN toughness values or hardness. In fact, Caltrans’ CVN data on four unfailed rods from S1 and S2 had nothing remarkably different from those that did fail, as discussed in 3.3.

Also, “1” contradicts “4.” As for “5,” the two PWS rods with rolled threads did not develop EHE cracks and therefore, they were “no tests,” which cannot be the basis for the statement of “5.” So are “6, 7 and 8.” The inconsistency of Caltrans’ interpretation methodology of the Test IV data may be summarized as follows:

(a) Rods #10 and 11, both 3.5 inch in diameter, fractured at 1.10 and 1.20Fu, respectively. In spite of the fact that they showed IGC, the last loading cycle before loading to failure was 0.85Fu. Caltrans assigned 0.80Fu as an EHE threshold stress for #10 and 11.

(b) Rod #1 fractured at 0.85Fu and had IGC. Caltrans gave 0.80Fu as an EHE threshold stress for #1.

(c) Rods #18 and 19 were step loaded in air. Since they fractured at 1.15Fu without showing IGC, Caltrans assigned 0.85Fu as an “IHE threshold stress” as if the IHE threshold stress is different from the EHE threshold stress.

(d) Rods #12 and 13 failed at 0.70Fu with IGC; thus, Caltrans assigned 0.65Fu as their EHE threshold stress. Rods #12, 13, 18, and 19 all came from the 32 HDG BD rods that failed on Pier E2 in March 2013 and had about the same hardness. Nevertheless, Caltrans found EHE and IHE threshold stresses ranging from 0.65Fu to 0.85Fu. In reality, the threshold stress for EHE should be about the same, including that for IHE threshold stress, if the hydrogen concentrations were above HTh.  

(e) Rods #10 and 11, both 3.5 inch in diameter, failed at 1.10 and 1.20Fu, respectively, and both showed IGC. Thus, Caltrans assigned 0.80Fu as an EHE threshold stresses because the last step loading cycle was at 0.85Fu.

(f) On the other hand, Rods #8 and 9 with rolled threads fractured at 1.10 and 1.18Fu, respectively, without IGC. So, Caltrans assigned an EHE threshold stress of 0.85Fu for #8 and 9.

(g) All these threshold stress determinations were done for 17 EHE threshold stresses and one IHE threshold stress irrespective of hardness/strength levels of the rod specimens and without hydrogen concentration analyses. Actually, the specimens that fractured without IGC (or other crack initiation/growth stage) during step loading cycles up to 0.85Fu should be treated as “no tests.”

4.2 Pretension Level Control – A Wrong EHE Prevention Methodology

The usefulness of above 0.70 – 0.85Fu as EHE threshold stresses for assuring no EHE failures with the HDG BD rods in the SAS is highly questionable. They are not even useful not only because the Test IV data do not support 0.70 – 0.85Fu as EHE threshold stresses, as discussed above, but also because the 7% (or 7 ksi) margin between 0.75Fu (105 ksi) EHE threshold stress for the 2,010 rods (point 1) and the
0.70Fu (98 ksi) pretension level for rods in Pier E2 is unjustifiably small. As discussed before, the 12 specimens that did not develop EHE cracks during the step loading cycle are simply “bad tests;” they cannot be interpreted to mean 0.85Fu (119 ksi) as an EHE threshold stress. The 0.75 – 0.85Fu EHE threshold stresses are also of little value in ascertaining no future EHE failures in the SAS. This is because Caltrans has neglected to take a number of uncertainty factors into consideration in arriving at this supposition that the 7% margin would provide a sufficient safety margin.

Just consider the most obvious and the most important factor in any “bolt-nut” connections: the effects of stress concentration on the local stresses at the roots of the threads and the stress distribution along the bolt axis after pretensioning using a nut, as illustrated in Figure 12 by Bickford. Referring to stresses in a bolt under tension, he stated, “the peak stresses (at the head fillet and nut-bolt engagement points) [are] two to four times the average stress in the body.”

Figure 13 shows more examples of stress concentration effects on the roots of the threads that are under tension by nut engagements. It is widely known that the stress at the root of the first engaged thread of the rod is higher than a global stress such as 0.32Fu used as a target value during pretensioning for the 3½ inch diameter PWS anchor rods (Group 7). Caltrans should have explained why the Test IV protocols would account for the stress concentration effects by the nut pretensioning (0.10 – 0.70Fu) in all cases in the SAS. Reference 8 has no discussions on the stress concentration effects by nut pretensioning.

For the PWS anchor rods, for example, which are pretensioned to 0.32Fu (45 ksi), the stresses at the roots of the rods under the nut engagement would reach 98 ksi (0.70Fu) or higher, limited only by local yielding. All that is required for these PWS anchor rods to fail due to EHE is for the susceptibility of the rod material (i.e., its local conditions) and the hydrogen concentration to be above threshold levels. The susceptibility of the PWS anchor rod material, particularly those with rolled threads, is unknown and the Test IV data have no definitive data that they are more resistant to EHE than cut threads. Contrary to what Reference 8 states, no one including Caltrans has data that support higher EHE threshold stresses for

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44 http://engr.bd.psu.edu/davej/icons/FEthreads.jpg
rolled threads than those for cut threads when compared for the same body hardness. In addition, the PWS anchor rods are not well protected from corrosion in the splay chambers, which will increase the hydrogen uptake.\textsuperscript{45} Wet conditions are also prevalent around the tower base anchor rod as well. Therefore, merely concentrating on and presenting a high EHE threshold stress value such as 0.75\textit{F}u will do no good for avoiding EHE failures in threaded connections.

This is why of three key ingredients, susceptibility, hydrogen, and stress, the most important one is not the pretension level; it is the susceptibility of the material to HE cracking. So, Caltrans has been pursuing a wrong target in trying to resolve the EHE failure problems in the SAS.

Stress concentration effects also account for the reasons why fatigue failures in pretensioned bolts occur at the first engaged thread as shown in Figure 14.\textsuperscript{46} Arrows A1 and A2 are match points before the fracture. Fatigue cracks initiated there before anywhere else because of the stress concentration effect shown in Figures 12 and 13.

Likewise, “hydrogen embrittlement fracture is controlled by local stress and local hydrogen concentration in the vicinity of the notch root.”\textsuperscript{21} EHE cracks would likely initiate at the first engaged thread root, just like in high cycle fatigue cracks in bolts, because of the stress concentration effects by nut pretensioning.

This local area with higher stresses happens to be also the same location for enhanced corrosion (and, therefore, a favored location of EHE cracking) because of the crevices that form between the male and female threads. These local conditions are so important as to affect the test results significantly. Caltrans has, however, ignored them and believes the 7\% (or 7 ksi) is a safe margin. It will not work.

During the July 24, 2014 presentation, Nader orally inserted the yellow highlighted words, below, while discussing the conclusion of the Test IV data. He stated, “Based on the above, [as Engineer of Record], it is concluded that the A354BD rods in service on the SAS are safe as they are not susceptible to SCC at the design loads and conditions.”\textsuperscript{47} This is, however, not a valid conclusion and will not resolve the serious concerns about the future EHE failure possibilities in the SAS. The eight point summary of the EHE threshold stresses, presented on page 19, is not supported by the data presented and discussed by Caltrans.

When the following factors have been taken into consideration, Caltrans has gained almost nothing from the $20 million test program. Caltrans has not done the tests that are necessary to state that 0.75\textit{F}u is a conservative threshold stress for all the HDG BD rods in the SAS. This cannot be established without first determining the highest hardness that exists in the installed HDG BD rods in the SAS. Caltrans, Engineer of Record for the SAS, and their contractors have not learned why they need to correlate the HE susceptibility or EHE threshold stresses of HDG BD rods in the SAS to their hardness distributions. In addition, Tests V and VI have limitations as supplementary to the Test IV data. This will be discussed in Section 5.0.

https://www.youtube.com/watch?v=Ho78Yppyc_1&feature=youtu.be, Nader inserted the highlighted words at 1:52:30
4.3  Validity of Test IV Protocols for Determining EHE Threshold Stresses for HDG BD Rods

4.3.1 Test IV Protocol Validity: Invalid

As Caltrans repeatedly stated, the test IV protocols are “unprecedented.” The Test IV protocols have never been tried before or scientifically proven to be valid by any one for determining EHE threshold stresses for threaded rods, studs, or bolts.

There have been no precedents wherein an EHE threshold stress has been determined directly from step loading hot dip galvanized threaded rods as specimens, with or without precracks. As a result, the Test IV protocols lack a benchmark to gage its validity, particularly for the 3 to 4 inch sizes. There are no ASTM standard test methods to which the Test IV protocols conform.

It was, therefore, incumbent upon Caltrans to prove that the Test IV protocols are scientifically valid, particularly when the cost outlay was as much as $20 million from a public source. Tests IV – VI could have been one of the most important landmark EHE tests for bridge engineering as well as for the bolting and construction industries. Test IV produced, however, results that are “weird.” For example, Rod #3 with 39 HRC should have developed EHE cracks (during Phase I); but it did not. Caltrans has not provided any explanation why this happened or has tried to understand why this happened (such as hydrogen concentration below $H_{Th}$).

Let’s compare the results from Rod #9 (3.5 inch PWS rod with rolled threads) with those from #11 (3.5 inch PWS rod with cut threads) in Table 5, as shown below.

<table>
<thead>
<tr>
<th>Phase No.</th>
<th>Group ID</th>
<th>Rod No.</th>
<th>Max Load %Fu</th>
<th>Field Max Hardness HRC @ 1/4” from O.D.</th>
<th>Lab Average Hardness HRC at Root</th>
<th>Impact Toughness CVN ft-lbs @ 40F</th>
<th>Potential at F/N/Al Load Volts vs Saturated Calomel Electrode</th>
<th>Intergranular Cracking Detected in SEM?</th>
<th>EHE Threshold %Fu</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWS 3.5”φ</td>
<td>7</td>
<td>9</td>
<td>118</td>
<td>36</td>
<td>39</td>
<td>36</td>
<td>-1.01</td>
<td>No</td>
<td>85</td>
</tr>
<tr>
<td>PWS 3.5”φ</td>
<td>11</td>
<td>120</td>
<td>37</td>
<td>41(14)</td>
<td>34</td>
<td>-0.92</td>
<td></td>
<td>Yes (10)</td>
<td>80</td>
</tr>
</tbody>
</table>

Questions:

(a) Why did Rod #11 reach 1.20Fu (or 169 ksi) at fracture when it developed IGC at 0.85Fu (or 119 ksi)?

(b) This would mean that the IGC region was so small as not to affect the fracture load because it was higher than 1.18Fu (154 ksi) for Rod #9 that had no IGC. What was the size of IGC in Rod #11? Was IGC detected only by SEM examination, with no visual indications? If the IGC really exists, did the acoustic monitoring detect the IGC initiation at 0.85Fu? What proof is there that supports that the IGC occurred at 0.85Fu?

(c) If an IGC initiation and growth stage was detected in Rod #9 at 0.85Fu (from acoustic signals), why was the load increased to failure before it had time to grow? Isn’t this an indication that the hydrogen concentration was still increasing and has not yet reached $H_{Th}$ when the rod was loaded to failure? This suspicion is supported by the fact that it broke at the first thread engaged by the nut. Reference 8 did not state which end it failed.

(d) If Rod #11 had been held at 0.85Fu for a longer time than 140 hours, could it have eventually failed at 0.85Fu rather than at 120%Fu?

(e) Could Rod #10 also have failed at 0.85Fu if held for a longer time?

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48 Ref. 8, p. 3-11.
The results on Rods #14 – 17 of Group 18 are reproduced below. These were included in Test IV to check the effects of HDG on HE cracking susceptibility. #14 and 15 were HDG whereas 16 and 17 were not HDG. All four rod specimens were made of 4340 rather than 4140. The latter is the steel of choice for all the HDG BD rods in the SAS although the former (i.e., 4340) would have been a better (and a more expensive) choice because of higher hardenability for large diameter rods (3 – 4 inches Φ). Caltrans has provided no explanation as to why the 4340 steel was chosen to determine the effects of HDG on EHE cracking susceptibility.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Field Max Hardness HRC at 1/4&quot; from O.D.</td>
<td>Lab Average Hardness HRC at Root</td>
<td>Impact Toughness CVN ft-lbs @ 40F</td>
<td>Potential at FIN/Al Load Volts vs Saturated Calomel Electrode</td>
<td>Intergranular Cracking Detected in SEM?</td>
<td>EHE Threshold %Fu</td>
</tr>
<tr>
<td>18</td>
<td>HDG</td>
<td>14</td>
<td>109</td>
<td>35</td>
<td>N/A</td>
<td>-0.96</td>
<td>No (8)</td>
<td>85</td>
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</tr>
<tr>
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<td>15</td>
<td>110</td>
<td>36</td>
<td>N/A</td>
<td>-0.94</td>
<td>No (8)</td>
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<tr>
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<tr>
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<td>N/A</td>
<td>-0.70</td>
<td>No (8)</td>
<td>85</td>
<td></td>
</tr>
</tbody>
</table>

As shown above, the Test IV protocols produced no differences in EHE threshold stresses between the four 4340 rods, #14 - 17. Test IV should have shown EHE threshold stress for #14 and 15 much lower than those for #16 and 17 according to what has been known in the literature, including the 1975 Townsend data. Caltrans has provided no explanations as to why Test IV protocols failed to distinguish the effects of HDG on the EHE threshold stresses. One obvious reason for the no difference between them is that the test protocols were invalid; none of the four rods developed EHE cracks. This is another point that counts against the validity of the Test IV protocols. Caltrans has not tried to understand or explain why this happened. This is unscientific.

Test IV is significantly different from several ASTM standard test methods for determining EHE threshold stress intensity factors such as ASTM E1681. The test specimens in ASTM E1681 are fatigue precracked for measuring the maximum load at which a crack extension does not occur or the maximum load at which a crack extension is not detected. In Test IV, the HDG BD rods, used as specimens, had no fatigue precracks and measured the minimum load at which cracks (intergranular or transgranular) initiated (below the yield stress).

Caltrans claims that the Test IV protocol has been validated as a method for determining the EHE threshold load or stress (σEHE) for the HDG BD anchor rods in the SAS span. This claim is based only on one account. Namely, the two 3 inch diameter HDG BD rods, #12 and 13, from one of the 32 HDG BD rods that failed on Pier E2 in March 2013, also failed at 0.7Fu in Test IV. This happens to be the same pretension level as that of the pretension level used for the 32 failed anchor rods in March 2013. Rods #12 and 13 for this claim, however, came from one failed HDG BD rod, S2A8, for shear Key S2, as shown below from Table 5 on page 14.

Caltrans made two rod specimens, #12 and 13, from the same rod, S2A8. The two test data are actually from the same rod, S2A8, as shown above. This is tantamount to basing the validity of the entire Test IV
data on one data point. Considering that the Test IV protocols are “unprecedented” and their validity has not been recognized or established as scientifically valid by other materials scientists previously, Caltrans must present more than just the two of the same data from the same rod to prove the validity of the test protocol. Having not done so is unrealistic and unscientific. This is particularly so because EHE (or SCC) threshold stress intensity factor determination usually involves considerable scatters in test data. This will be discussed more on page 38 (Lack of Consideration of Scatter and Probable Errors in EHE Threshold Data).

Caltrans must provide more support and reasons why the Test IV protocols are valid for the $\sigma_{\text{EHE}}$ determination of 2 to 4 inch diameter HDG BD rods than just the two data points from the same rod. There are several questions that Caltrans must address before the Test IV protocols may become acceptable as a scientifically valid methodology for determining $\sigma_{\text{EHE}}$ for large diameter HDG BD rods. Until this has been done satisfactorily, the conclusions and recommendations made by Caltrans in their BD evaluation draft report (Reference 8) are of little value and the integrity of the 2,210 HDG BD rods in the SAS remains unresolved.\(^\text{49}\)

### 4.3.2 Error Filled Data Presentation and Questionable Test Data

Figure 9 on page 16 includes two examples of errors in data presentation. As shown below, this figure involves numerous more errors. Fifteen of the 19 data points are plotted wrong.

\(^\text{49}\) 2,306 (total HDG BD rods in the SAS) – 96 (for S1 and S2 – abandoned) = 2,210
The data of column 10 in Table 5 were supposed be plotted against the hardness data of column 5 because the horizontal axis of the above figure is labeled, “Field Measured Rockwell C Hardness (HRC) – Maximum Value Near Edge.” In actuality, the hardness data in columns 5 and 6 were mixed up. As originally presented by Caltrans, the above figure would give an impression that the 19 test data points have covered the hardness range of the HDG BD rods in the SAS reasonably well. When corrected, however, it is a different story.

The four data points at far right, one each at 37.6, 38, 39, and 41 HRC, are among those that are plotted wrong. One of them, marked #7 at 38 HRC, is an extraneous dot for Rod #10, marked #7 at 33 HRC. When these four data points are removed or moved to their correct respective places, the above figure would cover a hardness range of 32 – 37 HRC. This hardness range is inadequate to cover all the HDG BD rods in the SAS. Figure 15 shows examples of hardness traverse curves of PWS (Group 7) and tower base (Group 12) anchor rods with hardness as high as 41 or 43 HRC, which are higher than covered by the 32 – 37 HRC range in Test IV.

The problem with the data in Table 5 or Figure 9 is that they do not allow an extrapolation of EHE threshold stresses to HDG BD rods with hardness of 41 or 43 HRC. The Test IV data have nothing to predict the EHE threshold stress for the worst-case hardness, for example for the PWS anchor rod with 43 HRC (Figure 15a). If the 43 HRC is correct, it would be possible that the EHE threshold stress could be lower than 0.70Fu, not 0.85Fu. This is because the higher the hardness, the lower the EHE threshold stress. To state that the PWS anchor rods have 0.85Fu as the EHE threshold stress, Caltrans must prove that the EHE threshold stress for an HDG BD rod with 43 HRC is 0.85Fu (119 ksi) or higher. This is inconsistent with the data in the literature, including that of the 1975 Townsend data. A best estimate for an HDG BD rod with 43 HRC near the surface is 20 – 40 ksi according to the literature, not 119 ksi according to Caltrans, for an EHE threshold stress for HDG BD rods with 43 HRC. Therefore, Caltrans’ statement that the EHE threshold is 0.75 – 0.85Fu for all the HDG BD rods in the SAS is not supported by the Test IV data.

Rods #18u and #18g may have been included to determine the effects of “u – ungalvanized” vs “g – galvanized.” The latter is supposed to be much lower in EHE threshold stresses. Yet, the data points for these in Figure 9 are virtually indistinguishable. In other words, the Test IV protocol failed to produce the effects of the zinc coating on EHE cracking. This occurred probably because both #18u and #18g failed to produce EHE cracks during the 572 hour step loading period up to 0.85Fu. This was partly due to the wrong choice of the specimens for the test purpose. (Their hardness may have been too low.)
Caltrans’ choice of 0.75Fu as “a conservative EHE threshold stress” for all the HDG BD rods in the SAS span is invalid for several reasons as discussed above.

One of the reasons for these invalid results could be that Test IV tries to measure the lowest tensile load at which EHE cracks initiate in the thread roots rather than the highest tensile load at which an existing fatigue precrack would not extend due to the EHE cracking mechanism. Since the HDG BD rod specimens for Test IV only had the stress concentration effects of a series of thread roots without (intentional sharp) precrack tips, the Test IV protocol is not the same as the 1975 Townsend paper in which he measured the static tensile loads (by bending) at which existing fatigue precracks began to extend. In ASTM F1624, to which Test V (Raymond Test) is conforming, $K_{EHE}$ is determined using fatigue precracked specimens and defined as “not [specimen] geometry dependent,” whereas $\sigma_{EHE}$ is listed as “geometry dependent.” It appears that the Test IV protocol, including its set-up, will need improvements.

Caltrans needs to determine why Test IV protocol produced data that may be invalid for producing the stated objective: “Establish threshold load levels for hydrogen embrittlement of full size diameter galvanized A-354BD Rods in the SAS” in Figure 8. Better still, Caltrans needs to pursue a different strategy to resolve the potential EHE failures of HDG BD anchor rods in the SAS. Reasons for this will be discussed in 7.0 Alternative Strategy to Tests IV and V on page 42.

4.3.3 More Errors

Caltrans draft report (Reference 8) contains various other errors. Some examples are as follows.

One of the conclusions of Caltrans’ report is as follows:

- Galvanized A354BD rods on the SFOBB-SAS shall be protected from exposure to water by having at least one supplemental barrier against moisture such as: dehumidification, paint system, grout, or grease caps. This is expected to ensure that the long-term capacity of A354BD rods is greater than 1.0 Fu.

The highlighted sentence above does not make sense. The “long term capacity” will be greater than 1.0Fu only if the HDG BD does not develop EHE cracking. No paint system can take a credit for increasing EHE threshold stresses as it is not a perfect moisture barrier against metal corrosion. Limited accessibility of the installed rod surfaces would severely limit the coating efficiency. These moisture barrier systems can increase the time to EHE failures. If an HDG BD is susceptible to HE cracking, however, none of the supplemental barriers listed, either singly or in combination, can prevent it from EHE failures.

The following statement is incorrect.

**RECOMMENDATIONS**

The testing program results show that the A354BD rods on the SAS exhibit hydrogen embrittlement thresholds that are higher than their pre-tension stress levels and therefore are safe against environmentally induced hydrogen embrittlement as long as the galvanized coating remains intact.

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50 ASTM E1681, “stress intensity factor threshold for environment assisted cracking, $K_{EAC}$,” is defined as “the highest value of the stress intensity factor (K) at which crack growth is not observed for a specified combination of material and environment and where the measured value may depend on specimen thickness.” This is essentially the same as what Townsend determined in his 1975 paper, which is referenced in ASTM A490. See p.5.
51 Ref 8. p.4-8.
52 Ref. 8, p.ES-4.
The zinc coating protects the steel from corroding; it will not protect the steel from EHE failures. Instead, the zinc coating, whether intact or not, will promote EHE failures. The seven rods that developed IGC during the Test IV should appear to have the zinc coating intact visually.

Besides, the zinc coating by HDG contains numerous microscopic cracks. Also, it could be easily damaged during handling and nut engagements. The amount of corrosion of the zinc coating could be very small and appear to be intact. Yet, the hydrogen that is generated during the corrosion will permeate through the zinc coating, diffuse into the steel substrate especially where the zinc coating is damaged, and will increase the hydrogen concentration of the steel substrate.

The photograph of the fracture face, at right, of 2 inch East Saddle Anchor Rod (14-III-1), and several others like this one in File E17 have yellow arrows that are supposedly pointing to the directions of fracture propagation. The two top arrows are pointing to wrong directions. Chung pointed out these errors two times before, including one time in a public meeting where Caltrans top engineers were present. These errors remain uncorrected in File E17 and appeared again in Reference 8.

The following statements would indicate the writer and reviewers of Reference 8 have misunderstood the reference cited.

The 1975 paper by Townsend has no data on IHE threshold stresses or $K_{\text{IHE}}$. The author of the reference compared “$K_{\text{SCC}}$” between bare and zinc coated specimens and found that the zinc coating, both hot dipped and electroplated, lowered “$K_{\text{SCC}}$” or increased the material’s susceptibility to EHE cracking significantly in the hardness range for Grade BD.

Besides, as mentioned before, the threshold stress for IHE would be the same as that for EHE for the same HDG BD rods of the same strength or hardness level. The main (probably the only) reason that Rods #18 and 19 did not show IGC and both failed at 1.15$Fu$ is that the hydrogen concentrations in the two rods were below $H_{\text{Th}}$. Therefore, both #18 and 19 were “bad tests.” Caltrans may not assign 0.85$Fu$ as their IHE or EHE threshold stress.

The following statement is misleading.

- The 2008 rods would not have failed if they were protected from water.

References:

53 Ref. 8, p. 2-34.
54 Y. Chung and L. K. Thomas: High Strength Steel Anchor Rod Problems on the New Bay Bridge, Rev. 1, November 12, 2013, p. 27, 83 http://docdroid.net/dxzl
55 Ref. 8, p. 3-14.
56 Ref. 8, p. ES-3
57 Ref. 8, p. ES-4
It was impossible to protect the 2008 rods from water. High strength steels that are susceptible to EHE cracking will fail during atmospheric services due to diurnal condensates, which form water film on metal surfaces. Exposure to a pool of water is unnecessary for EHE cracking to occur. It would have taken only a longer time to fail if S1 and S2 rods had not been exposed to a pool of water.  

This is very much a stress corrosion cracking issue, which is another way of saying an EHE issue in this case. The 3 and 4 inch diameter tower base HDG BD rods are pretensioned to 0.38Fu and 0.45Fu, respectively. Because of the stress concentration effects by the nut pretensioning, the local stresses at the root of the rod thread roots that are engaged by the nuts could exceed the yield stress, which would be higher than the EHE threshold stresses for some of those rods. The wet condition around the tower base anchor rods will cause the zinc coating and the rod steel to corrode, generating hydrogen, which will then diffuse into the rods. When the hydrogen concentration in the rods reaches $H_{TH}$, some of the tower base anchor rods that are high in EHE susceptibility will develop EHE cracking.

### 4.3.4 Comparison of Test IV Data with 1975 Townsend Data

Caltrans’ BD evaluation report (Reference 8) compared the EHE threshold stress data against the 1975 data by Townsend, as follows.  

> In 1975, K_{scc} thresholds for precracked, galvanized 4140 bars with a hardness of HRC 37 was found to be 30 KSI-in^{1/2} [3]. However, application of fracture mechanics equations fails to predict the observed EHE thresholds in terms of the fractional Fu observed for threaded rods. For example, the Bueckner equation for 3-inch-diameter rods with an EHE threshold of 0.75 Fu gives a value of 60 KSI-in^{1/2}, double that of precracked bars. This demonstrates that the fracture mechanics solutions are not sufficient to predict EHE thresholds for threaded rods that do not have pre-cracks, as suggested by the work of Olsen [5].


The above statements are a poor attempt by Caltrans at explaining why the Test IV data are out of line with those in the literature. Raymond, one of Caltrans consultants and one of the top experts on $K_{EHE}$ determination methodologies, stated that fracture mechanics is the key element as illustrated by one of his slides at right.

Also, the conclusion of the above paper by Olsen is as follows:

> **Conclusion Based on the Comparison of Current $Y(a/d)$ Solution Methods**

Comparison of the five methods to determine $Y(a/d)$ support the need for and guide further research focused on the smaller crack lengths within the (cold-rolled) threaded region of nut loaded bolts (Fig. 15).
Olsen acknowledged problems with different Y factor (or F factor) values arising from using different models of fracture mechanics in trying to prevent fatigue failures by estimating fatigue crack growth rates in roll threaded fasteners in aircraft. Olsen did not present any data or discuss problems in converting K (stress intensity factor, based on linear fracture mechanics) to σ (stress, based on the conventional mechanics of materials) or vice versa. Caltrans needs to understand the differences in the nature of K from σ. It would be erroneous to state, “fracture mechanics solutions are not sufficient to predict EHE thresholds for threaded rods that do not have pre-cracks, as suggested by the work of Olsen.” He never mentioned EHE in his paper on fatigue crack growth analyses. It appears that Caltrans engineers misinterpreted or misunderstood what Olsen presented.

The problem lies in the use of $K \approx 0.80(\%Fu)$ by Caltrans as shown in Figure 16. Caltrans states $0.75Fu$ is equivalent to $K_{EHE}$ of 60 ksi$\sqrt{\text{in}}$. This is actually incorrect. A correct conversion using the equation in Figure 16 would give 0.75Fu as being equivalent to 84 ksi$\sqrt{\text{in}}$. This is much higher than the 1975 Townsend data.

Actually, the conversion factor (e.g., 0.8 in Figure 16) is constant, but only for a given crack size. It varies depending on the crack size, shape, and orientation. Olsen stated that for the threaded region, a/d <0.1, “The Y solution for these five models in the threaded region ranges $0.6 < Y(a/d) < 3.3$ when the crack length approaches zero.”

Figure 18 presents Y or F factors for 4UN threads for 2.5 to 6 inches in diameter from Cipolla. Using the data in Figure 18, calculations of the conversion factors similar to that in Figure 16 are presented in Appendix B1.

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Figure 17 Single groove bar with a crack.

According to these results, a conversion factor of 0.8 is applicable to $a = 0.02$ inch. When $a = 0.005$ inch, the conversion factor is about 0.5.

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60 $K \approx 0.80(\%Fu) = 0.8 \times 0.75 \times 140 = 84$ ksi$\sqrt{\text{in}}$.
Caltrans’ EHE threshold stresses from Test IV data in Table 5 have been converted to $K_{EHE}$ using 0.5 as the conversion factor. The results, presented in Appendix B2, are plotted in Figure 19 below, superimposing the 1975 Townsend data.

In Figure 19, blue triangles represent the $K_{IEHE}$ (or $K_{EHE}$) corresponding to the $\sigma_{EHE}$ with IGC and red squares those corresponding to the $\sigma_{EHE}$ without IGC. All are higher than the bottom curve for $K_{IEHE}$ with zinc coating by Townsend. If the conversion factor of 0.8 by Townsend was used, the red and blue data points will move up from 50 – 60 ksi$\sqrt{\text{in}}$ to 90 – 100 ksi$\sqrt{\text{in}}$ as compared with 30 – 40 ksi$\sqrt{\text{in}}$ by Townsend (the bottom curve in Figure 19) for a hardness range around 32 – 37 HRC.

A more serious problem with Caltrans’ $\sigma_{EHE}$ data is that the red squares remain horizontal at 60 ksi$\sqrt{\text{in}}$ across the hardness range of 32 – 37 HRC and the blue triangles have no correlation with hardness. According to Townsend, the $K_{EHE}$ is supposed to decrease with increasing hardness as represented by Figure 20.\textsuperscript{59} The 1975 Townsend data are consistent and the Test IV data are not consistent with other $K_{EHE}$ data in the literature.

Figure 19 A comparison of the Test IV data with the 1975 Townsend data.

Caltrans’ Test IV data show an anomalous behavior when converted to $K_{EHE}$ and plotted against hardness. Thus, when compared with the data in the literature, the EHE threshold stress data from Test IV by Caltrans are anomalous and scientifically invalid. Caltrans needs to explain why the Test IV data on EHE threshold stresses do not relate to rod hardness when converted to EHE threshold stress intensity factors (Figure 19). There may be several reasons that contributed to this anomalous behavior as discussed below.
4.3.5 Probable Reasons for Caltrans’ Anomalous EHE Threshold Stress Data

(a) Lack of Proper Evaluation of Hardness Data

Material’s susceptibility to HE cracking in terms of $K_{EHE}$ is usually correlated to its hardness, ultimate strength, or occasionally yield strength. The 4140 steel is commonly used to produce HDG BD rods, including those in the SAS. This steel lacks, however, sufficient hardenability to render uniform tensile or hardness properties across the diameter, particularly for 3 to 4 inch diameter rods. Figure 21 illustrates a hardness profile across a 3 inch diameter HDG BD rod of 4140 steel. The hardness profile would be generally open U or V shaped when this steel is heat treated (i.e., hardened and fully tempered at 800ºF minimum) in accordance with ASTM A354.

The hardness requirement of 31 – 39 HRC applies to the mid-radius ($r/2$) location at one diameter away from either end of a rod. Because of the hardness gradient across the diameter, a 3 inch HDG BD rod with 38 HRC at $r/2$ could have 41 HRC at the body surface or 40 HRC at the root of the 4UNC threads. Both 41 and 40 HRC at or near the surface are still acceptable to the ASTM A354 requirement of 31 – 39 HRC at $r/2$. However, HDG BD rods with hardness higher than 34 – 35 HRC could be liable to fail due to EHE cracking during service. Caltrans should have imposed a maximum hardness that would make HDG BD rods not susceptible to EHE cracking.

Caltrans has a large number of field and lab hardness test data on the HDG BD rods in the SAS in File E17. As mentioned before, many of them have an M-shaped hardness traverse profiles as exemplified in Figure 22. These unusual or anomalous hardness distributions across the diameter could result if the tempering time was designed to be so short as not to allow the tempering effects to soak through the entire rod cross section. This would be contrary to the intent of the 800ºF minimum tempering requirement of ASTM A354. In other words, many of the HDG BD rods in the SAS do not meet the intent of the heat treatment requirement of ASTM A354 because the tempering effect took place only in the skin or surface layer.

To make the matter worse, Caltrans is unaware of the serious problems that have come about because of lack of proper evaluation of the hardness data that were generated. For example, consider the hardness data in Table 5. A portion of this table is reproduced below.

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62 Thread height is about 0.15 inch for 4UNC threads (major diameter = 2.997, minor diameter = 2.699 inches). The locations of columns 5 and 6 are comparable to one another.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span  

The hardness data of column 5 are different from those of column 6 by as much as 3 to 6 points in HRC numbers for the same rod specimen. The ¼ inch from the circumferential surface in column 5 is roughly equivalent to the thread root in column 6. It would be unreasonable to expect a hardness difference of 6 points in HRC at equivalent locations of the same HDG BD rod specimen. One or the other or both may be erroneous. Caltrans should have required more tests to find out the reasons for these differences in hardness and should have reported HRC numbers that are closer to each other, for example with a difference of 2 or less in HRC numbers, which would be more representative of the hardness of the rods tested. Otherwise, Caltrans should have explained why a 6 point difference in HRC is valid and acceptable. This will seldom happen, if ever.

Instead, Caltrans is apparently using any hardness numbers that a testing contractor reported without “a careful evaluation.” In the above examples, Rod #5 had no IGC. This would be reasonable and consistent with 34 HRC in column 5. If 40 HRC in column 6 at a thread root were correct, Rod #5 should have developed EHE cracks (or IGC) during the step loading cycles. So, either one or both hardness data could be wrong. Rods #10 and 11 would have the same predicaments. Whether Rod #7 did not develop IGC because its hardness was on the low end (32 – 35 HRC) or the no IGC reflects the beneficial effects of the residual compressive stresses in the surface layer of the rolled threads are undeterminable. These undesirable data resulted because the rod specimens were picked at random without specific objectives or anticipation.

This is unfortunate because one of the objectives of Test IV was to determine the differences in EHE threshold stresses between cut threads and rolled threads. Because Caltrans did not select the rod specimens carefully with respect to the hardness of the rods, the test data are open to question or useless. Caltrans has no solid data to claim that HDG BD rods with rolled threads have a higher EHE threshold stress than those with cut threads. As mentioned before, Caltrans still does not even have a hardness gradient data on HDG BD rods with rolled threads such as those indicated by the dashed lines in Figure 22b.

As another example of Caltrans’ lack of evaluation of hardness data, Figure 15a from File E17 is reproduced at right. It shows an HRC number difference of as much as 8 points at 0.5 inch from the surface between field and lab data.

These results should have called for retests of one or both until the two data are reasonably close to each other. While a 3.5 inch diameter HDG BD rod is not
completely uniform across the cross section, there are no metallurgical factors that can account for the large differences in hardness at the same location from the surface layer of the same rod. Therefore, the hardness data like those in Figure 15a had to be wrong. Caltrans should have at least explained why a difference of 8 points in HRC numbers can occur and, therefore, is acceptable as a fact. File E17 has many hardness data that do not make sense metallurgically. For example, many hardness traverse data on HDG BD rods would be flat across the diameter if plotted. Some would be convex at the center. This is why the hardness data in File E17 are not trustworthy. They should be evaluated and corrected where warranted.

(b) Random Selection of HDG BD Rods as Test Specimens

Test specimens should be selected by design rather than picked at random from whatever were conveniently available, particularly when only as few as 19 tests to be done in Test IV.

Townsend and others have well established that the higher the hardness, the lower the K_{EHE} or \sigma_{EHE}. To establish a minimum \sigma_{EHE} using the Test IV protocols, therefore, Caltrans should have chosen and tested the HDG BD rods with the highest hardness for a given size that can represent the HDG BD rods in the SAS. Instead, Caltrans used any HDG BD rods that were conveniently available to them without regard to their hardness properties. Thus, the test data may not be used to establish any trend in EHE threshold stresses with respect to hardness and allow an extrapolation to the worst case hardness scenario. It is apparent that Test IV was planned and executed without “a careful evaluation.” If Caltrans had to spend as much as $20 million, a new batch of HDG BD rods could have been produced for use as specimens to specific test requirements rather than picking up HDG rods from here and there. Thus, the results presented in Table 5 do not conform to the known behavior of K_{EHE} (or \sigma_{EHE}) and are of little value.

(c) EHE Failure Locations and Townsend Test Rig Construction

Figures 23 and 24 (next page) show the specimens that were cut from Rods #1 - 4 of the Townsend test.\textsuperscript{63}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{failure_loads.png}
\caption{Photographs from Rods #1 - #4 of Test IV. (a) shows the fracture face of probably Rod #4. The arrows in (b) point to fracture locations in the Grade BD rod specimens.}
\end{figure}

\textsuperscript{63} http://baybridgeinfo.org/rods/briefing and http://baybridgeinfo.org/media/video/9-dr-mazen-wahbeh
Caltrans’ post Test IV analysis did not identify the failure locations except for Rods #1 – 4 and 9. Rod #3 failed at the dead end and Rod #1 at the jacking end at 0.85Fu. Caltrans assigned an EHE threshold stress of 0.80Fu to #1. Figure 24b shows that the fracture face of #1 consists of three distinctive zones, I (IGC, cleavage, dimples), II (ductile – mostly dimples), and III (cleavage and ductile – dimples).

HE fracture morphology can vary with K levels; it will, however, not change abruptly, leaving a sharp demarcation line between them, for example between I and II, under a constant load, as shown in Figure 24b. Thus, it is possible that Rod #1 could have started IGC at 0.75Fu, forming zone I. When the load was increased, II was formed while at 0.80Fu, and III during the final loading to failure at 0.85Fu. If this were the case, Rod #1 should have 0.75Fu, not 0.80Fu, as the EHE threshold stress. Alternatively, it would be possible for II and III to form during the final loading cycle to failure. The answer as to which one is correct would have to come from the acoustic monitoring data. Caltrans has not explained why 0.80Fu, not 0.75Fu, is the correct EHE threshold stress for Rod #1.

As discussed before, because of the stress concentration effects by nut engagements, EHE failures would occur in the rod threads where the nuts are engaged as illustrated in Figures 23a and 24.

In the Test IV rigs, the nuts for the rod specimens are placed outside the saltwater chamber (Figure 25). A “vent hole groove” in the spherical washer allows the saltwater to reach the nut threads. “This is to ensure a flow of the NaCl solution to the first thread of the nut and remove any trapped air. After
verifying the flow of the NaCl solution, the groove is sealed with a piece of closed cell backer rod, which is held in place with plumber’s putty.” Figure 26 shows a stream of water from the “vent hole” in the spherical washer.

Caltrans has no means of checking if the first engaged threads of the rod specimens were continuously wet, providing the same corrosion potential at the roots of the rod threads engaged by the nuts as intended. If the vent hole had been inadvertently plugged up either by the putty or salt crystals that formed due to evaporation, the most critical location of the specimen for the EHE threshold stress tests is subjected to an environment different from what was originally intended. Perhaps, as many as 4 or 6 “vent holes” may have helped to ensure the critical thread roots of the rod were exposed to the electrolyte continuously. The space (or gap) between the male and female threads is so small that the saltwater may not be able to maintain the same oxygen content and corrosion potentials as in the chamber. (Why are the threads in Figure 26 white? Was a thread lubricant or sealant used? If yes, that would be another big factor that can cause “weird” results.)

Regarding the “corrosion chamber,” ASTM E1681 states as follows.

<table>
<thead>
<tr>
<th>6.4 Environmental Chamber—It is important that the environmental chamber does not influence the test results either by modifying the environment or the electrochemical potential of the specimen. …</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6.1 It is necessary to maintain enough solution in the environmental chamber to ensure that the crack-tip region of the specimen is immersed in the corrosive environment at all times and to ensure that the concentration of the electrolyte is not increased by evaporation. …</td>
</tr>
<tr>
<td>8.6.2 For tests involving sodium chloride solutions, replace the test solution at least weekly. It may be desirable to provide a circulation system to ensure a constant level of aeration of the bulk solution. The effects, if any, of aeration on KEAC measurements are complex and not completely understood. …</td>
</tr>
</tbody>
</table>

It is possible that the Test IV protocols did not conform to the above requirements.

(d) Lack of Hydrogen Content Analysis

Hydrogen analysis of the specimens was not included in the Test IV protocols. As a result, Caltrans does not know if Rods #18 and 19 did not develop IGC in air because of lack of hydrogen in the rod steel. Caltrans merely concluded that their IHE threshold stresses were as high as 0.85Fu while two other rods (#12 and 13) from the same group, having about the same hardness, were low in EHE threshold stress at 0.65Fu. This does not make sense because IHE threshold stress should be the same as the EHE threshold stress. For the HDG BD rod specimens, what matters is the hydrogen concentration being higher than Hth regardless of the source of hydrogen being internal or environmental.

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64 Ref. 8, p. 3-6
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

It is more likely that the hydrogen concentration in #18 and 19 was below \( H_{\text{Th}} \). This is the likely reason why these rods did not develop HE cracks or IGC. If they had hydrogen concentrations higher than \( H_{\text{Th}} \), they would have failed at the same stress as the EHE threshold stress because Rods #12, 13, 18, and 19 all were about in the same hardness range, 34 – 37 HRC, coming from the same “2008 batch.” It would be erroneous to state, “[the] IHE threshold [for the 2008 HDG BD rods] is 0.85Fu, which indicates that the 2008 rods in the field failed due to EHE.”

Regardless of whether a rod failed due to IHE or EHE, HE threshold stress would be the same. The difference between IHE and EHE is only in the source of hydrogen in the steel. So, Caltrans made double errors: first, assigning 0.85Fu as an IHE threshold stress for Rods #18 and 19 and second, using that data to state that the S1 and S2 anchor rods failed due to EHE. Caltrans was wrong on both accounts.

Regarding the S1 and S2 anchor rod failures in March 2013, Caltrans states further as follows:

“Given … that the IHE threshold for this group of rod is significantly higher than 0.65Fu, it can be unequivocally concluded that the rods in Phase 3 [Rods #12 and 13] failed solely as a result of EHE.”

This again demonstrates Caltrans’ lack of understanding of IHE vs EHE. The cause of the S1 and S2 rod failures was EHE because it was the only cracking mechanism that is consistent with the bottom threads as the failure location in all cases without exception. Whether IHE had a role in these failures or not cannot be determined with the data available to Caltrans (or to any one). It is possible that the 12 specimens did not develop IGC during the loading cycle because their hydrogen concentration was not high enough or the steel was low in hardness so that it was not susceptible to HE cracking. These are the probable reasons why the 12 specimens that had no IGC should be treated as “no tests.”

Townsend used 1 inch square bars in his 1975 hydrogen embrittlement research. Rod #7 was a 4 inch HDG BD rod. Its nominal cross sectional area is 12.6 in\(^2\). This specimen for Test IV was 12.6 times the specimen size used by Townsend in 1975. Yet, the holding time in the corrosion chamber was only doubled. Also, the ratio of the volume of the electrolyte/specimen size for Test IV may have been far smaller than that used in 1975. The Test IV protocols including the NaCl chamber size and the holding time had never been validated before. No tests have been run to show that a total of 572 hours in small 3.5%NaCl chambers would be sufficient for the hydrogen concentration in the large specimens to reach \( H_{\text{Th}} \). Furthermore, 17 of the 19 specimens were hot dip galvanized. Caltrans paid no attention to their zinc coating thickness, which would affect hydrogen permeation rates. Some of the HDG BD rods were removed from installation. This would mean that the rod surfaces including the threads were soiled or contaminated with oxidation products, thread lubricants, and other substances. All of these varied surface conditions would have affected the rate of hydrogen generation/adsorption/absorption by the rods, affecting the outcome of the EHE tests.

Therefore, a hydrogen analysis was essential to ensure that \( H_{\text{Th}} \) was satisfied for measuring EHE threshold stresses. Caltrans has, however, never considered this as essential and not done a single hydrogen analysis.

When an EHE test has been completed, a hydrogen analysis should have been run as soon as practicable. It is possible that hydrogen has diffused out of the rods after the tests by now. The results of the 12 rods that had no IGC may never be interpreted correctly for lack of hydrogen data. They fractured without IGC because either the hydrogen concentration was too low or they were not susceptible to EHE failures. Either way, the results are the same. Their tests must be considered as “no EHE threshold stress determinable.”

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65 Ref. 8, p. 4.8
66 Ref. 8, p. 3-12.
(e) Lack of Consideration of Scatter and Probable Errors of EHE Threshold Load Data

All field or lab test data involve scatter and probable errors in data. “Experimental SCC data is notorious for a wide range of scatter.” EHE has as many factors as SCC that would influence the test data, producing considerable scatter in data, as illustrated in Figures 27 and 28.

For Caltrans to claim that 0.75Fu is good enough for all the pretensioned HDG BD rod in the SAS, Caltrans needs to provide a reasonable estimate of probable errors of the EHE threshold load data so that 0.05Fu (or a 7% margin) is valid for all situations in the SAS. This is particularly so because Caltrans’ EHE test protocols are “unprecedented” and no one has verified its efficacy and validity. Also, the scatter in actual rod stresses from one rod to another, from a target load after hydraulic pretensioning, should have been taken into consideration.

In spite of this need, Caltrans believes only the two test data (Rod #12 and 13) from one S2 rod that failed on Pier E2 in March 2013 are sufficient to justify the validity of the Test IV protocols. These alone are insufficient to confirm the validity of the EHE test protocols that are “unprecedented,” meaning no one else has data that can help support the validity of the Townsend test protocols.

The 0.75Fu as the EHE threshold stress for HDG BD rods in the SAS has the same predicament. Caltrans needs to show why 0.05Fu or 7% margin is sufficient and why only 7 EHE tests with IGC are statistically valid as an EHE threshold stress for all the HDG BD rods, including the ones with 43 HRC, in the SAS.

4.4 Caltrans’ Remedial Action

An EHE threshold stress test is one of most complex materials property tests. Even materials testing laboratories specializing in both fracture toughness and corrosion can go astray in trying out new testing protocols. It is really unprecedented for any government agencies that are not in the business of conducting complex materials property tests to spend $20 million only to produce the results that are

worth next to nothing. The foregoing presentations and discussions have established that Caltrans’ Test IV has produced data that are not useful for solving the EHE failure problems with the HDG BD rods in the SAS. The reasons why this occurred (together with detailed discussions on the specific problem areas) were previously covered in Sections 3.4, 4.1, 4.2, and 4.3.

Normally, in a case like this, Caltrans would have to determine what went wrong, find out the reasons why, and repeat the tests using modified or improved protocols. In this case, however, it is not recommended that Caltrans try to redo the Townsend Test, using improved protocols, because it was a flawed strategy for resolving the concerns about the possible EHE failures with the HDG BD rods in the SAS. An alternative, perhaps a better and more cost effective, strategy to the HDG BD rod problems will be discussed in Section 7.0. This strategy will use the HE threshold stress intensity factor data and empirical hardness data already available in the literature.

5.0 LIMITATION OF TESTS V – VI, SMALL SPECIMEN TESTS

5.1 Limitation of Fatigue Precracked Specimen KEHE Tests

As presented in 3.4.2, the objective of Test V was to “verify Test IV [data]” and the 1975 Townsend data as being valid. The “motivation” of Test VI was to verify the Test V data.

First, Test V, using small specimens, cannot really verify the Test IV data using HDG BD rods as specimens. This is because the small specimens, less than ½ inch square, would only represent the properties of the specific location from which the specimen was taken in the anchor rod cross-section. It cannot represent the entire rod when the rod’s properties including EHE threshold stress would vary from the surface to the center. This is why ASTM A354 has the following statement.

6.3 … In the event that fasteners are tested by both full-size and by the machined test specimen methods, the full-size test shall govern if a controversy between the two methods exists.

When the full size specimen data from Test IV are invalid, the small size specimen data from Test V will have a limited value. This is particularly so when many anchor rods have the peculiar M-shaped hardness traverse curves, which will defy small specimen tests to predict the properties of a whole rod.

Second, the fatigue precracked specimens cannot determine KEHE for the cold rolled threads because the notch and fatigue crack would consume the cold worked layer. So, any data for the cold worked layer would have to come from the specimens without fatigue precracks, like the specimens with a thread profile shown in Figure 10b. There are, however, some problems with the test data as discussed below.

5.2 Unreasonable Test V Data from Specimens without Precracks

The Caltrans draft report (Reference 8) has the following statement in connection with the Test V data in Figure 3.2-14, which is reproduced as Figure 29 on the next page.

Figure 3.2-14 shows a plot of minimum Fu-EHE against HRC with 2010 Test V data adjusted to the corresponding Test IV rod potential and hardness as described above. Again, the Test IV data was preserved and the Test V data was adjusted for potential and hardness. The figure shows the range of values for each test series. These results also show all rods are significantly above the applied load demand in the SAS. Tables of results can be seen in Appendix M.
Since Appendix M is practically empty except for one page and Reference 8 lacks sufficient explanation about the Test V data, it is difficult to understand what the Test V data in Figure 29 displays. It is unclear if the data points in Figure 29 are from fatigue precracked specimens or from thread profile specimens. It is likely that Figure 29 displays the data from both types of specimens.

It is curious, however, how the several “EHE failure load” data points inside the blue circle at 33 – 34.5 HRC are so unreasonably high, about 50% higher than the tensile strength that was converted from the hardness of the specimen. This might indicate that either the Test V protocols or stress calculations may have problems. Also, data points #12 inside the red circle appeared to be plotted wrong, again, because there are no specimens that have 41 HRC as “field measurement.” The same error occurred with the Test IV data in Figure 9.

Regarding the Test V data, the Caltrans’ draft report states as follows.\(^69\)

The observations that can be drawn from these data are:

1. The results of Test V agree with the conclusions established in Test IV.
2. The results of Test V indicate the SCC threshold is greater than the applied loads for the SAS.

\(^{69}\) Ref. 8, p.3-29.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

The same two statements as above also appear as part of conclusions.

The above results by Test V are of little use because the Test IV protocols and most of the Test IV data appear to be invalid.

6.0 LITMUS TESTS FOR 0.75Fu AS EHE THRESHOLD STRESS FOR HDG BD RODS

For Caltrans to claim that Test IV and V data support 0.75Fu as a conservative EHE threshold stress for all the HDG BD rods in the SAS span and no HDG BD rods will fail due to EHE, Caltrans data must pass all of the following litmus tests.

(i) The 0.75Fu (105 ksi) as an EHE threshold stress is greater than the stresses that would develop at the roots of the rod threads when the rods are pretensioned to 0.70Fu (98 ksi) by nuts. Caltrans’ report has no discussions on the stress concentration effects by the nut pretensioning and how 0.70Fu pretensioning is still “safe” and acceptable.

(ii) Caltrans can identify the worst HDG BD rods in the SAS span in terms of EHE cracking susceptibility. This may be done by hardness ranking. However, it is unreliable because of frequent disparities between field and laboratory hardness results derived from the same anchor rod and because Caltrans has not demonstrated the field hardness data are valid. Also, whether or not the bottom ends of the tower base anchor rods could be exposed to seawater infiltration in time, if not already, must be made clear.

(iii) Caltrans has Test IV and V data for EHE cracking for the worst case HDG BD rod, for example a PWS anchor rod with 43 HRC as shown in Figure 15a. Caltrans has no KEHE or σEHE data for HDG BD rods with hardness as high as 43 HRC.

(iv) Caltrans has Test IV data that show the above HDG BD rod with 43 HRC has an EHE threshold load higher than 0.75Fu when the specimens failed at the threads engaged by a nut. Caltrans’ Test IV data ranged in hardness from 33 to 37 HRC in one set and from 35 to 41 HRC in another set for the same 19 HDG BD rod specimens.

(v) Caltrans has Test V data that show 0.75Fu is valid as an EHE threshold stress for all HDG BD rods including those with hardness at 43 HRC and the stress concentration effects at the rod thread engaged by the nuts have been accounted for. The Test V data appear to have stopped at 39 HRC.

(vi) Caltrans can demonstrate the 0.05Fu (or 7 ksi or 7%) margin is greater than the probable errors of the Test IV data and the stress variations in the rods after pretensioning. Caltrans has not presented any estimate of probable errors.

The main findings and conclusions formulated by Caltrans and the Engineer of Record cannot pass any one of the above litmus tests at this time.

The Test IV – VI program is costly and cannot guarantee an EHE threshold stress as being higher than the pretension stress for all HDG BD rods in the SAS span when the stress concentration effects have been taken into account. This is because Test IV, using full size anchor rods as specimens, cannot be so

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70 This is a different issue from SF Gate reports that water (probably not seawater) was found in the sleeves of the tower base anchor rods. [http://www.sfgate.com/bayarea/article/Corrosion-feared-as-water-leaks-into-Bay-5781911.php](http://www.sfgate.com/bayarea/article/Corrosion-feared-as-water-leaks-into-Bay-5781911.php)  
Caltrans has not responded to inquiries about the water tightness of the tower footing box (See Figure 31). A TBPOC engineer continues to avoid answering the same question.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

exhaustive as to provide an unequivocal answer to the EHE threshold stresses for anchor rods that have “unorthodox” M-shaped hardness distribution characteristics. Caltrans has no idea about the details of the actual heat treatment procedures that the rod suppliers used to produce the HDG BD rods with those M shaped hardness distribution curves.

Caltrans purchased a new batch of 3 inch diameter 4340 steel HDG BD rods. These rods also have M shaped hardness traverse curves. This means that Caltrans did not stipulate that the tempering should be complete throughout the cross section for the new 4340 steel rods. If this is the case (incomplete tempering), it is undesirable. Caltrans did not report the peak hardness in the M-shaped hardness data for the 4340 specimens. Whether the peak hardness such as 43 HRC at ½ from the surface matters much in EHE failures or not is unknown. The interior location of the peak hardness could initiate HE cracking if it can eventually satisfy \( H_{ih} \) and \( \sigma_{ih} \).

Test V, although a large number of specimens have been tested, cannot guarantee that they can represent all the unknown metallurgical conditions that exist in the large diameter anchor rods in Figure 2, particularly those with M-shaped hardness traverse curves.

Caltrans should, therefore, abandon the Test IV – VI program and adopt a different strategy that relies on the susceptibility of the anchor rod material to EHE failures. That is, Caltrans should rank the anchor rods in terms of EHE susceptibility and replace the ones susceptible to EHE cracking with new ones not susceptible to EHE cracking, for example using 32 - 35 HRC at or near the surface as the criterion.

7.0 ALTERNATIVE STRATEGY TO TESTS IV AND V

7.1 Use of High Strength Steel Rods Not Susceptible to EHE Cracking

ASTM A325, A354 Grade BC, and F1554 Grade 105 are generally considered safe, with or without HDG, from EHE failures during service. It is not too difficult to understand that shear keys S1 and S2 could have used 3¼ inch diameter Grade BC instead of 3 inch diameter Grade BD. The former provides 98% of the clamping force of the latter and the S1 and S2 base plates are sufficiently large to accommodate 3¼ inch diameter anchor rods. Even 3½ inch diameter Grade BC could have been used, if necessary.

A panel, chaired by Prof. DesRoches for the California Senate Transportation and Housing Committee, reviewed the issues raised by the HDG BD failures on Pier E2 of the SAS span. It issued a report, “Technical Review of Design and Construction of New East Span of San Francisco-Oakland Bay Bridge.” This report stated as follows regarding the selection of the 3 inch diameter HDG BD for the shear key anchor rods that failed in March 2013.

| 2. The required seismic capacity levels\(^\text{19}\) suggest that the use of similar diameter bolts made from a more traditional anchor bolt material (ASTM F1554 Grade 105) would have been sufficient. This material grade is known to be safe for hot-dip galvanizing, sufficiently ductile and not susceptible to hydrogen embrittlement. Use of ASTM F1554 galvanized bolts would have provided the same seismic performance without any of the additional risks associated with the use of galvanized A345 BD bolts. In hindsight, this approach may have provided a much simpler and a more reliable design. |

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\(^{71}\) Ref. 8, p.3-13.

In other words, HDG BD rods were not the only choice for the high strength anchor rods in the SAS span. Also, Caltrans can identify the anchor rods that may be susceptible to EHE failures during service. They could have replaced them with new ones not susceptible to EHE failures.\(^\text{73}\)

Table A1 of Appendix A shows that out of 2,306 HDG BD rods in the SAS, 1,135 may be replaceable. The others are either irreplaceable or could be excluded from future EHE failure concerns. Many items that require only 0.10 – 0.20Fu pretension could be excluded because their pretension stress would be below EHE threshold stresses. Perhaps, 30% of the 1,135 HDG BD rods or about 340 rods may require replacements because of potentially high EHE susceptibility based on (new) field hardness data. (Table A2 shows a “Primer,” probably meaning a paint system, is included as a “moisture barrier.” No paint systems will guarantee a consistent protection of HDG rods from EHE failures.)

It would be also possible to write a technical specification specifically for the replacement anchor rod applications. This would require the conformance to the minimum tensile strength requirement (e.g., 140 ksi minimum at mid-radius), 32 - 35 HRC maximum hardness at both ends of each rod, across the cross section, and full tempering with no M-shaped hardness traverse curves allowed. Anchor rods meeting these requirements can be hot dip galvanized and would be not susceptible to EHE failures during service, irrespective of the magnitude of pretensioning, up to 0.70Fu. No grease cans, additional coating, or dehumidifiers will be necessary on the HDG BD rods that are not susceptible to EHE failures. Actually, allowing for probable errors in hardness testing, 32 or 33 HRC maximum hardness requirement should be considered (for a new system or) if Caltrans can accept a lower minimum hardness from 31 HRC for BD to 28 HRC minimum at the surface. This is because the rod manufacturers would need some 4 to 5 points in HRC numbers between a minimum and maximum hardness range requirement. API RP 17A (ISO 13628-1) requires 32 HRC maximum for “subsea petroleum and gas production systems,” as follows.\(^\text{74}\)

\[
6.4.2 \quad \text{Bolting for structural applications should generally be of carbon or low-alloy steels, where the strength class should not exceed property class 8.8 for bolts in accordance with ISO 898-1}^{[1]} \text{ and property Class 8 for nuts in accordance with ISO 898-2}^{[2]}, \text{ with a maximum actual allowable hardness of 300 HBW or 32 HRC. The hardness shall be positively verified by spot hardness testing for each delivery, batch and size of bolts used.}
\]

This approach may be a more practical and cost effective means of eliminating the future EHE failure concerns of the HDG BD rods in the SAS. As mentioned before, however, Caltrans would have to redo the field hardness tests because what are available in File E17 are untrustworthy. In some cases, it may be practically difficult to do the rod replacement. Caltrans should, however, evaluate the feasibility of this strategy over the pretension stress control as the main means of preventing EHE failures with HDG BD rods in the SAS. Also, Caltrans should evaluate whether 32 or 35 HRC maximum is appropriate for replacement anchor rods in the SAS.

### 7.2 Risk Analysis of Tower Base Anchor Rods

The tower (T1) base anchor rods are not replaceable (Figure 30, next page). The 424 HDG BD rods for the tower base are inside the steel footing box shown in Figure 31 (next page). Being only several feet from seawater, the tower base anchor rods are subject to more severe marine atmospheric corrosion than at any other locations in the SAS. As can be seen in Figure A1 of Appendix A, the tower base is one of

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four locations in the SAS where the enclosed chambers are supposed to have air dehumidifiers. The dehumidifiers for the tower bottom were, however, not yet installed as of July 2014.

As can be seen in Figure 31a, the bottom half of the footing box is submerged in seawater. Caltrans and TBPOC engineers have continued to avoid answering a simple question: “Is the footing box watertight?”

The hardness data in File 17, examples presented in Figures 32 and 33, show 38 – 41 HRC as peak hardness near the surface for the tower base anchor rods. This hardness range indicates EHE failures are plausible with the tower anchor rods, both 3 and 4 inches in diameter.
Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

Figure 34a shows the 424 HDG BD rods and 150 dowels in the tower foundation. The four legs of the tower were lowered onto them as shown in Figure 34b. Typical top ends of the HDG BD rods for the tower are shown in Figure C2 of Appendix C.

![Image](image1.jpg)
(a) 424 HDG BD rods and 150 dowels for T1 in footing box

![Image](image2.jpg)
(b) First tower leg being lowered

Figure 34  Tower (T1) foundation with HDG BD rods and dowels in the footing box in (a) receiving the base of one of four tower legs in (b).

The footing box may not be watertight because the weld joints between the 13 pile steel shells and the steel box bottom may be not completely continuous. If this were the case, seawater will permeate through the concrete inside the footing box and will eventually reach the bottom ends of the 424 HDG BD anchor rods for the tower base. The 3 and 4 inch HDG BD rods are pretensioned to 0.48Fu and 0.37Fu, respectively, which could be sufficiently high to cause EHE failures. It may take years; but some of them that are susceptible to EHE cracking will eventually fail, particularly if exposed to seawater.

As shown below, the tower anchor rods were installed in 2006 – 2008 in the tower footing box and pretensioned in 2011.

<table>
<thead>
<tr>
<th>Item #</th>
<th>Fabricator</th>
<th>End of Fabrication</th>
<th>Tension or Loading Complete</th>
<th># of Rods Installed</th>
<th># of Fractured Rods After Tensioning</th>
<th>Days Under Tension Through July 1, 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Vulcan Threaded Products</td>
<td>Feb 2007</td>
<td>Mar 2011 0.48Fu 300 3&quot;φ</td>
<td>0</td>
<td>0</td>
<td>621</td>
</tr>
<tr>
<td>13</td>
<td>Vulcan Threaded Products</td>
<td>Feb 2007</td>
<td>Mar 2011 0.37Fu 300 4&quot;φ</td>
<td>0</td>
<td>0</td>
<td>621</td>
</tr>
</tbody>
</table>

In September 2014, Caltrans reported the results of inspection of the tower base anchor rods. According to Figure C1 of Appendix C, Caltrans found that “95% of rods were wet” and “138 rods [were] not fully grouted” up to 5.27m (17.4 ft). See Figure 35. Preliminary analysis results of the water samples from the tower base indicated 80 – 500 ppm chloride and 3 – 30 ppm zinc. These findings increase the concerns about the possibility of EHE failures of some of the tower base anchor rods.

Caltrans should do a risk analysis of the tower base anchor rods due to the possibility of future EHE failures.

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75 2014-09-30 TBPOC Tower Rods Final
8.0 CONCLUSIONS AND RECOMMENDATIONS

(1) Caltrans’ conclusions and recommendations in their September 2014 report on the A354 BD Rod Evaluation are incorrect and will not resolve the concerns about possible hydrogen embrittlement (HE) failures of hot dip galvanized (HDG) Grade BD rods that are critical to the structural integrity of the self-anchored-suspension (SAS) span.

(2) Caltrans concluded that a conservative threshold stress for environmental hydrogen embrittlement (EHE) cracking is 0.75Fu (105 ksi) for all the HDG BD rods in the SAS span and that these rods are safe as installed from EHE failures because they are pretensioned to 0.70Fu (98 ksi) or lower. (Fu represents the minimum specified tensile strength, which is 140 ksi for ASTM A354 Grade BD for sizes greater than 2½ inches in diameter.)

(3) The above conclusion is erroneous for three reasons: (1) The higher the strength (or hardness), the lower the EHE threshold stress, (2) Caltrans’ hardness data in File E17 indicate 43 HRC as the highest hardness for anchor rods in the SAS whereas the highest hardness of Caltrans’ EHE test specimens was 41 HRC, and (3) The 0.75Fu as the EHE threshold stress cannot guarantee no EHE failures for all HDG BD anchor rods in the SAS because the probable errors in HDG BD rod pretensioning and EHE threshold stress data would exceed the 0.05Fu (7 ksi or 7%) margin.

(4) Furthermore, the EHE threshold stress of 0.75Fu for all HDG BD rods in the SAS span is not supported by the Test IV data. It is likely based on erroneous data interpretations.

(5) Only 7 out of 19 EHE tests showed intergranular cracks (IGC) during the 572 hour step loading cycles. Assigning 0.85Fu as the EHE threshold stress for the specimens that did not show IGC (or other slow crack growth phase) during step loading cycles is unscientific and fictitious.

(6) Whether EHE cracking occurs or not is dependent on local stresses, local susceptibility, and local hydrogen concentrations. The 0.75Fu as the EHE threshold stress cannot guarantee freedom from future EHE failures in the HDG BD rods in the SAS because Caltrans has neglected to provide sufficient explanation about stress concentration effects by nut pretensioning, data scatter, and probable errors in data analysis.

(7) It is possible that the test environment (the 3.5%NaCl chambers) failed to conform to the requirements of ASTM E1681 for KEHE determination.

(8) The Test IV protocols are questionable or may be invalid as a methodology for determining EHE threshold stresses for HDG BD anchor rods in the SAS. No hydrogen analysis was included as part of the EHE test protocols. Lack of hydrogen content data was conducive to misinterpretation of the Test IV data.

(9) The Test IV protocols were “unprecedented.” It means no one else has established their validity as an EHE threshold stress determination methodology. Caltrans should provide more support for the scientific validity of the Test IV protocols than just two data points (Rod #12 and 13) from the same HDG BD rod (S2A8) that failed on Pier E2.

(10) A stress control in the pretensioned HDG BD rods as a means of EHE prevention is precarious and difficult to guarantee success consistently. Caltrans should abandon this strategy in trying to resolve the EHE failure problems with the HDG BD rods in the SAS.
(10) Instead, Caltrans should adopt the strategy of using HDG BD rods that are metallurgically not susceptible to EHE failures, for example those with peak hardness of 32 - 35 HRC maximum.

(11) Caltrans should identify HDG BD rods in the SAS that are susceptible to EHE failures and replace them with new HDG BD rods or equivalent rods not susceptible to EHE failures. The choice of the maximum hardness requirement (between 32 and 35 HRC) for replacement rods would require more evaluation of other factors not covered in this report.

(12) As for monitoring, Caltrans should concentrate on the tower base anchor rod performance because they are not replaceable and their failures would be critical to the SAS structural integrity. If the bottom ends of the tower base anchor rods could become wet with seawater eventually, some of them will eventually fail due to EHE. It may take years but it is difficult to predict the timeframe of EHE failures. Caltrans should develop a risk analysis of the tower base anchor rod performance.
Appendix A

Table A1 Breakdown of HDG BD Rods in the SAS Span

<table>
<thead>
<tr>
<th>ID</th>
<th>Structural Component</th>
<th>Year</th>
<th>Number of Bolts</th>
<th>Diameter [in]</th>
<th>Bolt Tension @ Service % Fu (UTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shear Key Anchor Bolts — Bottom (S1/S2)</td>
<td>2008</td>
<td>96</td>
<td>3</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>Shear Key Anchor Bolts — Bottom (S3/S4)</td>
<td>2010</td>
<td>96</td>
<td>3</td>
<td>0.70</td>
</tr>
<tr>
<td>3</td>
<td>Pier E2 Bearing Bolts — Bottom Housing (B1, B2, B3, B4)</td>
<td>2010</td>
<td>96</td>
<td>3</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>Shear Key Anchor Bolts — Top (S1/S2)</td>
<td>2010</td>
<td>160</td>
<td>3</td>
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| Fu (Tensile Strength) per ASTM A354-11 | Total: 2,306 |

Caltrans has not discussed whether the three saddles at W2 are dehumidified or not to protect the PWS from atm corrosion. “7” has two locations, East and West. So, four chambers need to be dehumidified to protect the HDG BD rods (7 and 14-15) and the PWS.

Figure A1 Locations of HDG BD rods in the SAS

Items 1, 5, 6, 9.5, 10, 11, 14, 15, 16, 17 (96+96+336+8+90+4+32+18+24+43 =747) may be excluded from EHE failure evaluation because their pretension levels are 0.20Fu or lower, they are internal to bearings, or abandoned in the case of item #1.

2306 (total) –747 (above exclusion) – 424 (tower base anchor rods – irreplaceable) =1,135 (replaceable)
Various Methods to Protect HDG BD Rods from EHE Failures in the SAS by Caltrans\textsuperscript{76}

<table>
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<tr>
<th>Group ID</th>
<th>A354 BD Bolt Location</th>
<th>Tension (%Fu)</th>
<th>Dehumidified</th>
<th>Primer</th>
<th>Grout</th>
<th>Grease Caps</th>
<th>Supplemental Moisture Barrier</th>
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\textsuperscript{76} A354BD Rods Presentation TBPOC 8-28-14
Appendix B

Table B1
Shape factors $F \sqrt{a}$ for crack depths $a = 0.005 \sim 0.100$ inch using Cipolla’s approximations in ASTM STP 1236

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<th>Rod size inch</th>
<th>D Major Dia</th>
<th>d Minor Dia</th>
<th>R Min root radius</th>
<th>D/d</th>
<th>d/D</th>
<th>t/d</th>
<th>a Crack depth</th>
<th>a/d</th>
<th>F</th>
<th>$F' = F \sqrt{a}$</th>
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Validity of Caltrans’ Environmental Hydrogen Embrittlement Tests on Grade BD Anchor Rods in the SAS Span

Appendix B

Table B2

Caltrans Test IV Data on Hardness and %Fu converted to $K_{EHE}$ using a shape factor for 0.005 inch deep initial cracks

| Phase No | G’p No | Rod No | Specimens ID 3”Ø with cut threads unless otherwise noted | HRC Field ¼ in From OD | HRC Lab At Th’d root | I G C | Load at fracture %Fu | $\sigma_{EHE}$ ksi | $\sigma_{EHE}$ ksi | $K_{EHE}$ ksi√ι
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<td>13</td>
<td>Shear Key S2 (2008) bottom</td>
<td>34 35 √ 70 65 91 46</td>
<td>34 35 √ 70 65 91 46</td>
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<td>4 18</td>
<td>14</td>
<td>2013 Galv (4340)</td>
<td>37 NA 109 85 119 60</td>
<td>37 NA 109 85 119 60</td>
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<td>15</td>
<td>2013 Galv (4340)</td>
<td>36 NA 111 85 119 60</td>
<td>36 NA 111 85 119 60</td>
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<td></td>
<td>16</td>
<td>2013 UnGalv (4340)</td>
<td>37 NA 113 85 119 60</td>
<td>37 NA 113 85 119 60</td>
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<td></td>
<td>17</td>
<td>2013 UnGalv (4340)</td>
<td>36 NA 115 85 119 60</td>
<td>36 NA 115 85 119 60</td>
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<td>5 1</td>
<td>18</td>
<td>Shear Key S1A7 failed rod</td>
<td>36.5 NA 115 85 119 60</td>
<td>36.5 NA 115 85 119 60</td>
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<td>19</td>
<td>Shear Key S2H6 failed rod</td>
<td>36.5 NA 115 85 119 60</td>
<td>36.5 NA 115 85 119 60</td>
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</tbody>
</table>

*%Fu = 150 ksi for diameters ¼ - 2½ inch inclusive and 140 ksi for diameters > 2½ inch.

Phase 1: Rods 1 through 4
- 2010 – 3” dia. E2 Lower Shear Key and Bearing Rods (4 rods - cut threads)

Phase 2: Rods 5 through 11
- 2010 – 2” dia. Upper Bearing Rods (rolled threads)
- 2006 – 3” dia. Tower Base Rods (cut threads)
- 2010 – 4” dia. Tower Saddle Tie Rods (rolled threads)
- 2010 – 3.5” dia. PWS Rods (2 with cut and 2 with rolled threads)

Phase 3: Rods 12 and 13
- 2008 – 3” dia. Shear Key Rods (from fractured rods)

Phase 4: Rods 14 through 17
- 2013 – 3” dia. E2 Shear Key and Bearing Rods (cut threads, galv. and ungalv.)

Phase 5: Rods 18 and 19
- 2008 – 3” dia. Lower E2 Shear Key Rods in the dry
Appendix C

Recap of September 2014 TBPOC Meeting

- 95% of rods were wet
- 138 Rods not fully grouted
  - 6 rods ranging from 2.17 m to 5.27 m ungrouted
  - 12 rods ranging from 350 mm to 600 mm ungrouted.
- 66 Samples of Water Collected
  - 10 samples sent for chemical testing
  - 1 sample bay water sent for chemical comparison
  - 4 samples sent for biological testing

Figure C1 Caltrans’ inspection results of tower anchor rods in September 2014.

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77 2014-09-30 TBPOC Tower Rods Final
Appendix C

Figure C2 Typical installation of tower anchor rods at the top ends.