HIGH STRENGTH STEEL ANCHOR ROD PROBLEMS ON THE NEW BAY BRIDGE

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Revision 1

November 12, 2013

Prepared for

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HIGH STRENGTH STEEL ANCHOR ROD PROBLEMS ON THE NEW BAY BRIDGE

ABSTRACT

On July 8, 2013, the Toll Bridge Program Oversight Committee (TBPOC) released its report on the high strength steel anchor rod failures on Pier E2 of the new Self Anchored Suspension (SAS) Bridge in the San Francisco-Oakland Bay. This TBPOC report was based largely on a metallurgical failure analysis report of May 7, 2013, authored by one Caltrans engineer (A), one consultant (B) to American Bridge-Fluor Joint Venture, and one consultant (C) to Caltrans. This report is referred to as the ABC report in this review.

This report presents the results of a critical review of both the TBPOC and the ABC reports. The purpose is to point out numerous errors including the erroneous conclusions as to the cause of the shear key anchor rod failures and serious questions about the long term performance of anchor rods for the main cable and the tower base.

This review discusses how the TBPOC's ABC metallurgical team arrived at the wrong conclusion and how the TBPOC made several metallurgically flawed statements in the TBPOC report and during several briefings to the Bay Area Toll Authority (BATA). Other documents and presentations that the TBPOC and Caltrans have released since the shear key anchor rod failures in March 2013 and an FHWA review report have also been included in this review.

Both the ABC and the TBPOC reports lack thoroughness in metallurgical investigations and contain numerous errors, both editorial and technical. More importantly, they overlooked one of the most important aspects of the failures: all 32 rod failures occurred in the bottom threads. Not only did the TBPOC fail to explain this most peculiar failure pattern but also completely ignored the significance of this failure pattern. This led them to incorrectly conclude the cause of the failures: [short-term] hydrogen embrittlement or internal hydrogen embrittlement (IHE). Consequently, the remedial decisions, including "new supplementary requirements" for replacement anchor rods, have been proposed (and may have already been implemented) even though they lack sufficient technical references or justifications.

Furthermore, many errors and questionable test data discussed in this review and poor engineering and construction skills throughout the new Bay Bridge project demonstrate that the "Caltrans Insular Culture" needs to be changed. There is the need for a "meaningful reform at Caltrans" before they are allowed to take on another mega-project for the State of California.

We recommend that the Transportation and Housing Committee of the California State Senate reject the July 8, 2013 TBPOC report as an unacceptable public document and request that the TBPOC issue a new revised report. Several reasons for this recommendation are presented.

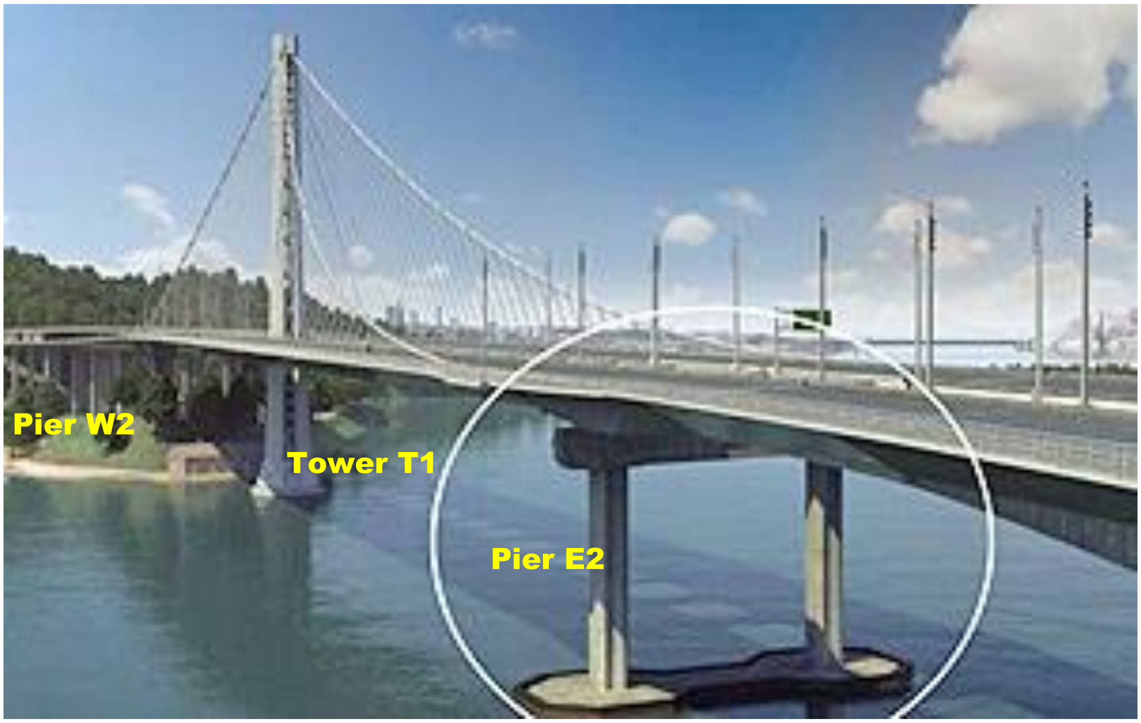
Summary of Revision 1

Page No.	October 28, 2013 Original Issue	November 12, 2013 Revision 1
ii	Bernard R. Cuzzilo, Ph.D.	Bernard R. Cuzzillo, Ph.D., P.E.
2	$20 million	$23 million
4	192 items	193 items
16	caustic and nitrate stress corrosion cracking of steel	intergranular stress corrosion cracking (IGSCC) of stainless steels
26	have been The Caltrans	has been the Caltrans
50	(page 70)	(page 71)
53	not A354	not ASTM 354

List of Peer Reviewers

The following professors and engineers have reviewed this report and concurred with the recommendations of this report.

	Names	Job Title/Affiliation
1	Robert G. Bea, Ph.D.	Professor Emeritus, Civil and Environmental Engineering University of California, Berkeley
2	Bernard R. Cuzzillo, Ph.D., P.E.	President (Mechanical Engineer) Berkeley Research Company
3	Harold J. Mantle	Chief Materials Engineer (Retired)
4	Cory Padfield, P.E.	Lead Materials Engineer
5	Patrick Pizzo, Ph.D.	Professor Emeritus, Materials Engineering San Jose State University



Tower T1 and Piers E2 and W2 of the Self Anchored Suspension (SAS) Bridge

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1.0 INTRODUCTION

The Toll Bridge Program Oversight Committee (TBPOC) has managed the construction of the new East Span of the San Francisco-Oakland Bay Bridge (SFOBB) since 2005.

In early March 2013, it looked as if the new East Span with the iconic Self Anchored Suspension (SAS) Bridge might soon open with a gala celebration, on the day after Labor Day in September, as scheduled. Then, it happened. On March 27, 2013, TBPOC/Caltrans announced that 32 of the 96 anchor rods for Shear Keys S1 and S2 on Pier E2 of the SAS Bridge had failed under static load within two weeks after they were pretensioned.[1] Actually, the S1 and S2 anchor rods were pretensioned to 0.7Fu (70% of the specified minimum tensile strength or 140 ksi) between March 2 - 5, 2013; the broken rods were found between March 8 - 14 (Figure 1a).[2] The remaining 64 unbroken rods were detensioned to 0.4Fu on March 15 in order to prevent them from failing.

A series of events since then have revealed a serious weakness in materials engineering expertise not only at Caltrans and its contractors but also in other government agencies. Several major reports released as public documents were littered with errors, both editorial and technical, which underscores the concerns expressed in the media about Caltrans' insular culture that has allowed a large scale project to proceed in spite of flaws in checks and balances in their Engineering-Construction skills.

The anchor rods for the base plates of Shear Keys S1 and S2 were each 3 inches in diameter. Sixty (60) of the 96 were 17 ft long (about 400 pounds each).[3] The remainder (36) were 10 ft long (about 240 pounds each).[4] Figure 1b shows the distribution of L1 (17 ft) and L2 (10 ft) anchor rods in S1 and S2 base plates. These anchor rods, each with both ends threaded for about a foot, were produced to the requirements of ASTM A354 Grade BD and hot dip galvanized (HDG).[5]

The SAS Bridge has 2306 HDG Grade BD rods, including the 96 for the S1 and S2 base plates. They are identified as Item No. 1 – 17 in Figure 2.[6] Of these, about 1600 rods are located on or around Pier E2.

Pier E2 has four Shear Keys, S1 – S4, and four bearings, B1 – B4 (Figure 3a). These are major mechanical devices that would restrict the lateral and vertical movements of the traffic decks during an earthquake. Each shear key is anchored to the cap beam of Pier E2 with 48 anchor rods and each bearing with 24 anchor rods. These anchor rods are 3 inches in diameter and 10 to 23 ft long (Figure 3b). Figure

[1] In Reference 6 below, the TBPOC defined the Shear Key as follows:

Shear Key A shaped joint between two prefabricated elements that can resist shear through the geometric configuration of the joint.

The above defnition of a shear key as a shaped joint does not fit the description of S1 – S4, which are mechanical devices on Pier E2.

[2] 4/10/13 BATA Oversight Committee Meeting Materials. These dates are March 1 – 5 and March 8 - 15, 2013 in Reference 7. http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_A_BATA_Meetings/A-2_BATA_Meeting_April_10_2013.pdf

[3] Gerdau Heat No: M644914.

[4] Gerdau Heat No: M644912.

[5] ASTM A354 Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners. (ASTM: American Society for Testing and Materials.)

[6] http://www.mtc.ca.gov/projects/bay_bridge/A354_report.pdf

3c shows a typical anchor rod detail for Shear Keys S1 and S2. The anchor rods for B1 – B4 and S3 and S4 would go through the cap beam of Pier E2 from the top surface to the bottom surface.

Shear Keys S1 and S2 are located directly above the two piers that support the cap beam. Since the bottom ends of their anchor rods, each 10 to 17 long, would have to be inside the cap beam of Pier E2, they were placed inside grout pipes when the reinforced steel concrete cap beam was produced (Figures 3b and 3c). Because of construction delays, the 96 anchor rods for Shear Keys S1 and S2 remained inside the grout pipes of the cap beam for some five years. When they were pretensioned in early March 2013, 32 of the 96 anchor rods failed as mentioned earlier. As indicated in Figures 3b and 4, all 32 failures occurred in the bottom threads.

Figure 5a shows the anchor rod lay out in the base plate of Shear Key S1. When an anchor rod fails under pretension or under static load, its top end would pop out as shown in Figure 5b.

To replace the clamping force lost by the anchor rod failures for Shear Keys S1 and S2, both are clamped down to the cap beam of Pier E2 using saddles and post tension (PT) tendons (Figures 6 – 8). This fix is going to cost around $23 million.

The TBPOC released on May 8, 2013 a metallurgical failure analysis report on the 3 inch diameter HDG Grade BD anchor rod failures. This report, "Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6,"dated May 7, 2013, will be referred in this review to as the ABC report, using the last name initials of the three engineers who authored it.[7,8] As shown in Figure 1b, 45% of L1 (27 out of the 60 rods) and 14% of L2 (5 out of 36 rods) failed. The ABC report covers only two failed L1 anchor rods, one each from S1 and S2. None of the unbroken rods were evaluated. In spite of the clearly different failure rates between L1 and L2, the ABC team did not examine any of L2 rods, broken or unbroken.

The ABC report concluded that the 32 anchor rods failed due to hydrogen embrittlement (HE). It did not clarify, however, whether the failures were due to internal hydrogen embrittlement (IHE) or due to environmental hydrogen embrittlement (EHE). The TBPOC report stated, however, that HE is a short term phenomenon and referred to EHE as "*long term stress corrosion cracking*." Thus, "short term hydrogen embrittlement" is IHE in the context of the TBPOC report.

The distinction between IHE and EHE is based on the source of the hydrogen, not on the time to failure after pretensioning. IHE is associated with the hydrogen that entered the steel during the anchor rod manufacturing processes. EHE is associated with the hydrogen that entered the steel from the environments during service. It will be shown in this report that IHE is the wrong conclusion.

On July 8, 2013, the TBPOC presented its own report with the following title:[9]

Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge, With Findings and Decisions

[7] 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_Fracture_Analysis_Report.pdf

[8] ABC stands for the three authors of the above metallurgical failure analysis report: Aguilar (Caltrans Engineer), Brahimi (Consultant to American Bridge/Fluor Joint Venture), and Christensen (Consultant to Caltrans).

[9] http://www.mtc.ca.gov/projects/bay_bridge/A354_report.pdf

This TBPOC report has repeated much of the findings of the ABC report and presented additional test data and decisions on what to do about the 2306 HDG Grade BD rods on the SAS Bridge. This report will be referred to as the TBPOC report here. A review of this report disclosed 42 simple errors (typographical and editorial), listed in Table 1, 16 confusing or inconsistent use of terminology (Table 2), and 135 erroneous or technically questionable statements (Table 3). Some are metallurgically untenable.

There are serious questions as to the long term performance of the anchor rods for the main cable and the tower base. The reasons for these concerns have been also discussed in this review.

Then, as "an arm's length peer review," the TBPOC requested the Federal Highway Administration (FHWA) to review the TBPOC report, including the "Findings and Decision," and other test data.[10] The FHWA complied with the TBPOC request with the following report by a seven member team:[11]

San Francisco-Oakland Bay Bridge Seismic Safety Project
FHWA Review of the A 354 Grade BD Bolts Used in the Self-Anchored Suspension Bridge
August 2013

In a letter to the TBPOC Chairman on August 9, 2013, the California Division Administrator of the FHWA stated as follows:[12]

> We have concluded both reviews and agree with the approaches. We concur with the disposition of the bolts/rods and the recommended course of action described in the TBPOC's final report dated July 8, 2013, as shown in Table ES-2 and subsequent language on pages ES-16 and 17.

The FHWA was in full agreement with the TBPOC with no recommendations for correction of errors, verification of questionable test data, or erroneous interpretations. Conversely, the TBPOC's decision to replace all of the 740 HDG ASTM A354 Grade BD rods of Items #2, 3, 4, and 11 on Pier E2 was apparently endorsed by one of FHWA recommendations, as follows:[13]

> 2. Use the Greg Assessment Tool *[See Appendix B]* developed by FHWA for determining the vulnerability of the bolts to hydrogen embrittlement or stress corrosion cracking.

In this review, the reasons why the Greg Assessment Tool lacks technical justification and the reasons why the TBPOC's decision to replace the 740 large HDG Grade BD rods lacked technical merits and a diligent evaluation will be discussed.

This report also discusses (1) major technical errors, shortcomings and oversights in the ABC report as well as the TBPOC report, (2) reasons why the conclusions of the ABC and the TBPOC reports are wrong

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[10] http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_D_Correspondence/D2_FHWA_Letter.pdf
[11] http://www.mtc.ca.gov/pdf/FHWA_SAS_Bolts_Report_August_2013_-1.pdf
[12] http://www.mtc.ca.gov/pdf/FHWA_SAS__Review_Letter.pdf
[13] Item #2 Bearing and Shear Key Anchor Rods, 192, 3"ϕ x 22 – 23 ft long; Item #3 Shear Key Rods (Top), 320, 3"ϕ x 2 – 4.5-ft long; Item #4 Bearing Rods (Top), 224, 2"ϕ x 4-ft long. All three items are pretensioned to 0.7Fu, fully exposed to the atmosphere.

regarding the metallurgical cause of the S1 and S2 shear key failures, and (3) why most of the new supplementary requirements for replacement Grade BD anchor rods will be ineffective.

The July 8 TBPOC report is unacceptable as a public document that closes out the $6.4 billion project. The report must be error free, editorially and technically. In view of the numerous errors, including the conclusions, and technically questionable statements in the ABC and the TBPOC reports, the TBPOC must issue a revised report on the S1 and S2 anchor rod failures on Pier E2.

Table 4 presents the questions that the TBPOC/FHWA need to address before their reports, together with findings and decisions, may be deemed acceptable regarding their validity and accuracy.

Lastly, this report points out that the shear key anchor rod failures on Pier E2 in March 2013 are a tip of a larger problem: the insular culture at Caltrans that has allowed incompetent engineering decisions repeated one after another for many years. This would indicate a systematic symptom and there is the need for a reform at Caltrans.

2.0 ERRORS IN THE TBPOC AND THE METALLURGICAL REPORTS

Both the TBPOC and the ABC metallurgical reports contain numerous errors, from a simple editorial type, including typographical, to significant technical errors. The errors and questionable statements in the TBPOC report are listed in Tables 1, 2, and 3, for 193 items. Of these, 135 are technical errors or technically questionable statements; some are metallurgically untenable, and many are indicative of lack of basic understanding of the metallurgy of high strength steels. They are marked by *'s for over 40 items, including mix-ups between stress and strength in five places, to be discussed in Section 2.10.

Previously, Chung sent his review report, "Comments on Caltrans' Metallurgical Report on Pier E2 Anchor Rod Failures," to Caltrans.[14] He pointed out six simple editorial errors (e.g., psi for ksi, two places, grain direction for a grain flow direction, etc.), ten statements that required clarification, including Conclusions 1 and 3, and questionable specimen preparation (i.e., hard surface grinding) for hardness testing that might have resulted in erroneous hardness data. One of them was included in Slide 23, shown in Figure 9, as one of the important findings by the Caltrans Director during the July 10, 2013 BATA Briefing. In this presentation, in reference to the two hardness graphs in Figure 9, the Caltrans Director stated as follows:

> "… You can see the hardness numbers [of the "Other 3" Rods] are significantly better than the hardness numbers of the 2008 bolts, ah, the representative of the 2008 bolts on the left that broke. …"

He made two errors in this statement, as follows:

(1) The one on the left in Figure 9 is from a single rod that failed. It is not representative of "the 2008 bolts," but may represent one of the worst ones of the 32 rods that failed. It does not represent the

[14] http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_D_Correspondence/D7_Report_and_Letter_from_Yun_Chung.pdf

remaining 64 rods of 2008 that did not fail. In fact, the Caltrans' metallurgical team, ABC, had none of the 2008 rods that did not fail included in their metallurgical failure analysis of the S1 and S2 anchor rod failures. This omission reflects scientific diligence in ABC's metallurgical investigation was lacking, especially since it was simple to obtain samples from the top ends of these rods for examination.

(2) The one on the right in Figure 9 represents average data of several lots of the "Other 3" Rods" that had highs and lows for individual rods. It is improper to compare the hardness traverse data of a single rod that failed against average hardness traverse data of a lot of many rods that did not fail. Therefore, Slide 23 may not be used as a support for "Improved Hardness" for the "Other 3" Rods."

In addition, both the TBPOC and the ABC reports contain serious oversights and wrong conclusions as to the metallurgical cause of the S1 and S2 anchor rod failures on Pier E2. Some of their major errors and oversights are discussed below.

2.1 New Jargon - "Long-term Stress Corrosion Cracking" and "Affinity for Hydrogen"

Every professional field uses jargon. Every engineering discipline has its own jargon. They are "the language used for a particular activity or by a particular group of people"[15] or "special words or expressions that are used by a particular profession or group and are difficult for others to understand."[16] Jargon changes over time, however, when the understanding of certain aspects of a particular jargon changes, for example when new scientific evidence emerges. Hydrogen embrittlement (HE) and stress corrosion cracking (SCC) are such jargon of materials science or more specifically of corrosion science. For high strength steel failures under static load at room temperature, what used to be referred to as stress corrosion cracking in the 1940 – 1970's changed to hydrogen embrittlement cracking (and its variations) when the role of hydrogen in the failure mechanisms was better understood in the 1980's.

High strength steel failures under static load, particularly in atmospheric services, used to be referred to as SCC, even though those failures had no visible signs of corrosion such as rusting. HE or its variation such as hydrogen cracking or hydrogen assisted cracking became preferred to SCC when hydrogen was identified as the causative species of the cracking. Although SCC is not incorrect, it covers a broad range of conditions in which high strength steel and many other alloys can fail under static tensile load below the yield strength of the material. HE can be defined to a much narrower and specific set of conditions than SCC, specifically for high strength steel failures at room temperature. Curiously, however, the TBPOC report has invented a new jargon, "*long-term stress corrosion*." It provides no clear meaning of what it represents; it is not used in the contemporary materials-corrosion science literature.

Below is a definition of SCC by the ASTM.[17]

> **stress corrosion cracking (SCC)**—a cracking process that requires the simultaneous action of a corrodent and sustained tensile stress.

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[15] http://www.merriam-webster.com/dictionary/jargon

[16] https://www.google.com/webhp?sourceid=navclient&ie=UTF-8#q=jargon

[17] ASTM: American Society for Testing and Materials.
ASTM F2078 Standard Terminology Relating to Hydrogen Embrittlement Testing.

SCC involves some aspects of corrosion. IHE does not involve corrosion. Also, of structural failures due to SCC, Copson stated, “one of the curious aspects of stress corrosion cracking is the wide difference in time required for failure, which varies from a matter of minutes to many years.”[18] Since the time to failure can vary over a wide range, materials engineers or corrosion scientists seldom refer SCC to as a short-term or a long term phenomenon in formal technical reports.

For SCC to occur in metals and alloys, a specific chemical species is required such as chlorides for SCC of austenitic stainless steels. For high strength steels, hydrogen is one of several species that can cause SCC. The limitation (or the Achilles heel) of high strength steels is that they can fail due to SCC under static stresses, sometimes far below their yield strength. When high strength steels fail during service in atmospheric or aqueous environments at ambient temperature, their failures were previously classified as SCC in the 1950 – 1970’s because corrosion scientists were uncertain as to hydrogen as the causative agent and as to the role of hydrogen in the cracking mechanism in the high strength steel failures under static load.

In a keynote speech at the 1980 Symposium on “Hydrogen Embrittlement and Stress Corrosion Cracking,” Professor Herbert Johnson of Cornell stated, [19]

> “Studies of water-induced cracking in high strength steels have shown that subcritical growth and delayed failure of high strength steels in water environment are caused by hydrogen, discharged from the water by the reaction with the steel.”
>
> “Their experiments [referring to Professor Troiano and his students] removed the major objection to the concept that hydrogen is a causative factor in many examples of stress corrosion cracking.”

So, the term *long-term stress corrosion cracking* of high strength steel rods on Pier E2 by the TBPOC is not different from hydrogen embrittlement (HE) cracking. Therefore, the SCC of high strength steels due to hydrogen has been more commonly referred to as HE cracking rather than SCC in the contemporary materials engineering literature. A few exceptions may still be found, however, like those in a corrosion chapter of some civil engineering books that have not been updated since the 1980’s. This is discussed in Section 2.9 (p.15) of this report.

TBPOC's invented term "*long-term stress corrosion cracking*" is unnecessary and without technical merit. It does not appear in the contemporary materials science literature. Such practice only obfuscates the already difficult-to-understand subject of hydrogen embrittlement cracking of high strength steels.

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[18] H. R. Copson: The Influence of Corrosion on the Cracking of Pressure Vessels, The International Nickel Company, Inc., Reprinted from the Welding Journal, February 1953 Supplement.
Copson is a co-author (with LaQue) of “Corrosion Resistance of Metals and Alloys,” Reinhold, 1963. While working at the research laboratory of International Nickel since 1934, Dr. Harry Copson published many technical articles on galvanic corrosion, atmospheric corrosion, and stress corrosion cracking. He was the recipient of the 1946 Dudley Medal Award (Charles Dudley – a founding member of the ASTM in 1898 and its president in 1902 - 1908) of the ASTM and of the 1961 Willis Rodney Whitney Award “in recognition of his public contribution to the science of corrosion” by NACE (National Association of Corrosion Engineers).

[19] R. Gibala, R. F. Hehemann: Hydrogen Embrittlement and Stress Corrosion Cracking, A Troiano Festschrift, ASM International, 1985 First Edition, 2002 6th Printing.
Professor Herbert Johnson served as Director of the Materials Science and Engineering Department from 1970 to 1974, followed by as Director of the Materials Science Center until 1984, both at Cornell University.

2.2 Distinction between Internal Hydrogen Embrittlement (IHE) and Environmental Hydrogen Embrittlement (EHE)

High strength steels have been known to fail under static load when three conditions are simultaneously satisfied: material's susceptibility to HE above a threshold level, hydrogen concentration above a threshold level, and stress above a threshold level. If these conditions are satisfied for high strength steel, microscopic cracks will form at points of stress concentration such as at a thread root. The microscopic cracks will grow larger over time under static load well below the yield strength of the metal. When the hydrogen-assisted crack has grown to a critical size and the remaining intact cross section cannot withstand the static load, a final fracture occurs instantaneously.

The source of hydrogen determines whether the failure is IHE or EHE, as defined below by the ASTM.[20]

> **internal hydrogen embrittlement (IHE)**—hydrogen embrittlement caused by absorbed atomic hydrogen into the steel/metallic alloy from an industrial hydrogen emitting process coupled with stress, either residual or externally applied.
>
> **environmental hydrogen embrittlement (EHE)**—hydrogen embrittlement caused by hydrogen introduced into a steel/metallic alloy from an environmental source coupled with stress either residual or externally applied.

Time to failure does not distinguish IHE from EHE. The dividing line between IHE and EHE is in the source of the hydrogen, not in the time to failure. If the failure of a high strength steel rod can be attributed to the hydrogen that was already present in the rod at the end of the rod manufacturing processes, including hot dip galvanizing (HDG), the cause of the failure would be IHE. In contrast, if the source of hydrogen is the environment, for example, from a corrosion reaction after rod's final manufacturing processes, the cause of the failure would be EHE. It is this simple. The dividing line between IHE and EHE does not have to involve the time to failure. Thus, the new term, "*long-term stress corrosion cracking*" by the TBPOC is contextually inappropriate in addition to being confusing. EHE and IHE can be operative over a range of time, from weeks to years.

There is really no mystery why EHE failures can take longer than IHE failures. Both EHE and IHE involve a crack initiation and growth stage as assisted by hydrogen in the steel. In the case of IHE, the hydrogen that can do the crack initiation and growth is already present in the steel. In the case of EHE, the steel must go through the time to be charged with hydrogen from the environment in which the steel dwells. This can take time, depending on the environment to which the steel is exposed.

2.3 EHE and TBPOC's Long-term Stress Corrosion Cracking

In the TBPOC report, EHE is referred to as "*long-term stress corrosion cracking,*" stress corrosion cracking (SCC), or just stress corrosion, probably because the hydrogen was supplied by a corrosion

[20] Ref. 17.

process of the zinc coating, the steel substrate, or both. The use of the term, "*long-term*" or "*longer-term*" is rarely used in combination with SCC but understandable in a way because SCC failures (or EHE failures) would take a longer time than IHE failures, as discussed above. IHE failures usually occur in minutes to weeks after high strength steel rods have been pretensioned to above a threshold stress level and if the rods can simultaneously satisfy two additional conditions: hydrogen concentration above a threshold, and susceptibility above a threshold.

Conversely, EHE failures manifest themselves usually after a longer period, extending into years and decades, particularly in atmospheric services. This is mainly because it takes time for the corrosion process that may produce hydrogen as a byproduct to occur and it takes time for the gradual accumulation of hydrogen that entered the steel to reach above a threshold level. There is no predictive model that works well to tell when or whether EHE (or SCC) failures might occur in high strength steels. This is because many environmental factors would interact with one another during the hydrogen generating-charging (or uptake) process. This is also one of the reasons why no accelerated SCC tests, such as the Townsend Test, can be completely successful in trying to simulate actual long term environmental corrosion process.

As mentioned already, the long-term SCC of high strength steel rods in the atmosphere involves hydrogen as the causative species. SCC is not different than EHE in high strength steel failures under static load in this regard. It will be shown next that the 32 anchor rods for S1 and S2 failed due to EHE, or long-term SCC as defined by the TBPOC, not due to "*short-term hydrogen embrittlement*" or IHE as concluded by the ABC report and the TBPOC report. This is the most important error of the TBPOC and the ABC reports.

As discussed above, what separates IHE from EHE is not the time to failure from the time a high strength steel rod was pretensioned until it failed under a static load. The time to failure as to a short-term or a long-term as described by the TBPOC is immaterial. In fact, the TBPOC cannot define what a "*long-term*" is, other than implying "over years or decades." That does not help or provide any clear advantages over the terms like IHE or EHE. "*Long-term stress corrosion cracking*" is nebulous as a descriptor because it encompasses a wide range of environmental conditions and materials, not necessarily limited to high strength steel. Conversely, IHE or EHE is specific to a clearly defined set of failure mechanism of high strength steel at room temperature. Referring to EHE as "*long-term stress corrosion cracking*" not only does not make sense but also is like going back in time for no good reason.

Since HE comprises IHE and EHE, it is confusing when the TBPOC stated, for example, "As used in this report, hydrogen embrittlement is considered a *short-term phenomenon* that occurs in metals, including high-strength steel, ..."[21] Then, the TBPOC goes on using "*near-term hydrogen embrittlement*" and "hydrogen embrittlement" interchangeably. Conversely, in a number of places in the TBPOC report, the term hydrogen embrittlement must mean both IHE and EHE. Examples are as follows:[22]

1. The April 2000 update of the Caltrans Bridge Design Specifications Manual prohibits the galvanization of A354 grade BD rods due to hydrogen embrittlement problems.

[21] Reference 9, p. ES-6
[22] ibid, p. 33,

2. ASTM A354 guidelines caution the use of hot-dip galvanizing on A354 grade BD materials, because the process could make the steel more susceptible to hydrogen embrittlement.
4. General industry concern over hot-dip galvanizing of A354 grade BD rods, including suppliers that will not galvanize this type of high-strength fastener[6].

While ASTM A354 cautioned that hot-dip galvanizing of A354 grade BD materials could make them more susceptible to hydrogen embrittlement, the guidelines did not preclude galvanizing.

Therefore, it would not make sense to call EHE as *long term stress corrosion cracking (SCC)* or long term SCC. The reason is that HE, IHE, and EHE is specific to high strength steels, mostly in air or water, and EHE failures will always take longer than IHE failures, whereas SCC can occur in a broad range of ferrous and nonferrous alloys in various environments and can occur in a wide range of time span as stated by Copson.[18]

The inconsistent use of various nomenclatures for the same phenomenon, HE, is unscientific and is confusing and unproductive in understanding the anchor rod failure problems in the TBPOC report.

2.4 Effects of Stress on Hydrogen Entry into Steel during IHE or EHE

In the above definition of IHE by the ASTM, the "industrial hydrogen emitting process" would include acid cleaning, commonly referred to as acid pickling, to descale the steel surface in preparation of hot dip galvanizing (HDG) or electrolytic plating. In these processes, during which the metal reacts with the electrolyte (including water), hydrogen is generated and can enter the steel while the steel is under no applied stress.

As for the effects of stress on hydrogen entry into steel, Gangloff stated as follow: "Stress is not necessary during hydrogen uptake."[23]

In the definition of EHE above by the ASTM, the environmental source that can supply hydrogen would include corrosion of steel, zinc, or both in water or in moist air, during which hydrogen can be generated as a byproduct. The ASTM definition of EHE sounds, however, as if stress is a prerequisite for this hydrogen to be introduced into the steel. This is not the case. The hydrogen entry into the steel from outside is governed by a diffusion process as influenced by hydrogen concentration gradients. It does not matter if the steel members are under stress or not for hydrogen to enter the steel to cause EHE, just as the stress was not a prerequisite for hydrogen to enter the steel in the case of IHE.

Stress is a prerequisite for IHE or EHE cracking to occur, but not for the hydrogen charging. Hydrogen can enter the steel whether it is under stress or not or before being pretensioned or after being pretensioned. This was one of the most important errors of the ABC report when it stated,

[23] R. P. Gangloff: Hydrogen Assisted Cracking of High Strength Alloys, 4/1/03, p. 7 of 194.
Dr. Gangloff is Professor of Materials Science and Engineering (MS&E) at the University of Virginia since 1990. He served as Chair of the MS&E Department. http://www.virginia.edu/ms/pdf/CV%20RPG.pdf
http://www.virginia.edu/ms/faculty/gangloffCSIChapterFinalProofed.pdf

> "EHE is caused by hydrogen introduced into the metal from external sources ***while it is under stress,*** such as is the case with an in-service fastener."[24]

It does not matter if the steel is under stress or not for hydrogen to be introduced into the steel.

It is clear that the metallurgical team, ABC, of the TBPOC misunderstood the role of stress in EHE. Since the steel can be charged with hydrogen during pickling while it is under no applied steel, later causing IHE, the same thing can happen in the case of EHE. Stress will help mobilize or transport hydrogen within the steel and help the hydrogen to concentrate at areas of high stresses such as points of stress concentration. Stress is, however, not a necessary component for hydrogen to enter the steel. Even the ASTM Committee who gave the above definition of EHE did not anticipate the scenario in which high strength steel members such as the S1 and S2 anchor rods would be exposed to corrosion in stagnant water for several years before they are pretensioned. This is, however, what happened to the anchor rods for Shear Keys S1 and S2 on Pier E2 of the SAS Bridge.

The above misunderstanding of the role of stress on hydrogen entry into the steel was crucial because it was the beginning of the wrong conclusion that the 32 anchor rods for Shear Keys S1 and S2 failed due to HE, which meant IHE rather than due to EHE (or the *long-term SCC* in the TBPOC report). This will be elaborated on more later in this report. This wrong conclusion has affected many aspects of the TBPOC report including its decisions to replace 740 anchor rods (the so-called "2010 rods" as opposed to the "2008 rods") and to issue several supplementary requirements for new replacement rods. These supplementary requirements are mostly unnecessary, except for a new hardness range (31 – 35 HRC) as discussed in Sections 2.13 and 2.15 of this report.

2.5 Misdiagnosis of the Cause of the Shear Key S1 and S2 Anchor Rod Failures on Pier E2

Since the steel can be charged with hydrogen during acid pickling while it is under no applied stress, later causing IHE when subsequently pretensioned, the same thing can happen in the case of EHE. The same thing happened to the anchor rods for Shear Keys S1 and S2 on Pier E2 of the SAS Bridge, causing them to fail due to EHE, not due to IHE (or short-term HE as defined by the TBPOC) in March 2013.

The TBPOC report adopted the four conclusions of the ABC report.[25] Conclusions 1 and 3 relate to the metallurgical causes of the S1 and S2 anchor rod failures, as follows.

> 1. *The anchor rods failed as a result of hydrogen embrittlement (HE), resulting from the applied tensile load and from hydrogen that was already present and available in the rod material as they were tensioned. The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement.*
>
> 3. *The metallurgical condition of the steel was found to be less than ideal. More precisely, the microstructure of the steel is inhomogeneous resulting in large difference in hardness from center to edge, and high local hardness near the surface. As an additional*

[24] Reference 7, Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6, page 9. The italics and the underline are added for emphasis in this review.
[25] Reference 7, p.12.

> *consequence of the metallurgical condition, the material exhibits low toughness and marginal ductility. The combination of all of these factors has caused the anchor rods to be susceptible to HE failure.*

Conclusion 1 is correct in so far as pointing out that "anchor rods failed as a result of hydrogen embrittlement (HE)." The next phrase, "from [the] hydrogen that was already present and available in the rod material as they were tensioned," is problematic. This phrase would be true for IHE. The ABC report did not state, however, that the S1 and S2 anchor rod failures were due to IHE. This is rather curious because the ABC report did discuss correctly what IHE is and what EHE is. If it is not IHE, it had to be EHE. The problem is that the above phrase about hydrogen could be also true for some special case of EHE. Therefore, Conclusion 1 is so unclear about IHE or EHE as the cause of the failures that it is unacceptable.

The next statement is even more problematic. "The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement." This is problematic because the ABC report did not define what is meant by "normal susceptibility of the steel to hydrogen embrittlement." Normally, the susceptibility of steel to hydrogen embrittlement is very low, almost zero. This is fortunate and the reason why the world is full of steel structures. Also, the susceptibility of Grade BD to HE will vary depending on the surface hardness from 31 to 39 HRC. Grade BD's susceptibility to HE may not be definable as to "normal" or "higher than normal." Therefore, Conclusion 1 makes little sense and is unacceptable.

Likewise, Conclusion 3 is unacceptable. No consensus can be established as to what would constitute an ideal metallurgical condition. The microstructure of the anchor rod steel, 3-inch round 4140, quenched and tempered, will have a range of microstructures that will be inhomogeneous, "resulting in [a] large difference in hardness from center to edge." This is illustrated in Figure 10, which shows a typical hardness traverse of a 3-inch round 4140 steel, quenched and tempered.

The HRC numbers cited in Figure 10 are actual lab test data from the ABC report. The hardness of a 3 inch anchor could vary from 39 HRC at the surface to 35 HRC at mid-radius (R/2) and to 30 HRC at the center (or core). The hardness decreases from the surface to the core as a result of different cooling rates that different locations would experience when the rod is hardened by quenching in an oil bath from around 1600ºF. The larger the rod diameter, the slower the cooling rates, resulting in lower hardness.

The changes in the metal hardness from the surface to the core are accompanied by changes in the microstructure, tensile strength, ductility, toughness, and other metallurgical properties or conditions. It is impossible for a 3 inch round 4140 steel anchor rod, heat treated to meet the tensile strength requirements of ASTM A354 Grade BD, to have a uniform microstructure across the diameter. So, the microstructure being "inhomogeneous resulting in [a] large difference in hardness from center to edge" may not be cited as a significant factor that contributed to the metallurgical condition being "less than ideal."

Low toughness and marginal ductility may influence the critical size of the HE crack zone but have no significant effects on HE crack initiation and growth rates. For example, alloys with higher toughness and ductility than the failed S1 and S2 anchor rods could also fail due to HE. Therefore, the several metallurgical factors mentioned in Conclusion 3 are inappropriate as the reasons for the supposition that the susceptibility of the S1 and S2 anchor rod steel to HE was high because of them. Also, the "low toughness and marginal ductility" are inappropriate as the cause of the failures because their values were obtained from a surface layer rather from a mid-radius location, which is the specified location for tensile specimens in ASTM F606.[26]

The TBPOC accepted the above conclusions by ABC as stated and adopted them as their own in the July 8, 2013 TBPOC report. In so doing, the TBPOC offered no modifications or elaborations. Instead, the TBPOC clarified the cause of the S1 and S2 anchor rod failures, probably without realizing what they were really saying, as follows.[27]

> **Summary of the TBPOC Investigation**
>
> Hydrogen embrittlement is the root cause for the failure of the A354 grade BD high-strength steel anchor rods at shear keys S1 and S2 (Item #1 in Table ES-1). As used in this report, hydrogen embrittlement is considered a short-term phenomenon that occurs in metals, including high-strength steel, when three conditions apply: a susceptible material, presence of hydrogen and high tensile stress (as shown in Figure ES-4).

The statement highlighted above clearly indicates that the TBPOC interpreted Conclusion 1 of the ABC report to mean that the S1 and S2 anchor rods failed due to "short-term HE," which is the same as IHE in this context. The TBPOC clearly did not associate the S1 and S2 anchor rod failures on Pier E2 with the "*long-term stress corrosion cracking*" or EHE.

The following statements by the TBPOC further confirm that they believe the S1 and S2 anchor rods failed due to IHE.[28]

> Upon completion of all the testing and implementation of mitigating measures as depicted in Figure 33, the risk of hydrogen-associated damage to the metallurgical structure of the high-strength rods will have been addressed for the SAS Bridge. These test results also provide conclusive evidence that the cause of the high-strength rod failures observed in March 2013 from short-term hydrogen embrittlement is isolated to the shear key S1 and S2 anchor rods at the top of Pier E2 manufactured in 2008. This conclusion is further confirmed by the ongoing performance of the remaining rods under varying levels of tension as depicted earlier in Table 9.

It is true that the S1 and S2 anchor rods failures were "a short-term phenomenon" because they occurred within two weeks of having been pretensioned. This does not mean, however, their failures were due to IHE because the hydrogen that was responsible for the crack initiation and growth during the two weeks before the final fractures did not come from the rod manufacturing processes. The reasons are as follows.

According to Brahimi, "Lower hardness specimens, in the range of 37 HRC are not embrittled by the galvanising process. This finding supports the contention that most high strength structural fasteners can

[26] ASTM F606 Standard Test Method for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets.
[27] Reference 9, Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge with Findings and Decisions, p.ES-6.
[28] ibid, p. 66.

be safely galvanised."[29] "Lower hardness steel, in the range of 25-38 HRC is typically not embrittled by the galvanizing process, as evidenced by the fact that most high strength structural fasteners can be safely galvanized."[30,31] Since the surface hardness of the two failed anchor rods, S1G1 and S2A6, was 36 - 38 HRC, these rods are unlikely to have failed due to IHE. Also, it is reasonable to expect more hydrogen can enter the steel from environments than from anchor rod manufacturing processes. The five year idling period that the S1 and S2 anchor rods experienced inside grout pipes provided a unique environment that allowed the bottom threads to be charged with hydrogen.

2.6 Fallacy of "Short-Term HE" (or IHE) as the Cause of S1 and S2 Anchor Rod Failures

The ABC report concluded that the S1 and S2 anchor rods failed because of hydrogen embrittlement (HE) and the TBPOC report clarified the HE as "a short-term phenomenon," which would be the same as internal hydrogen embrittlement (IHE). The TBPOC referred to environmental hydrogen embrittlement (EHE) as "*long-term stress corrosion cracking*."

If indeed the S1 and S2 anchor rod failures were due to short-term HE or IHE, the rod manufacturer should be held accountable for these failures. In that case, the hydrogen that did the crack initiation and growth had to have been introduced into the steel during the rod manufacturing processes. Still, the TBPOC did not cite the rod manufacturer as being responsible for supplying the ASTM A354 Grade BD rods that had a high concentration of hydrogen.[32] Thus, the TBPOC contradicted itself. To state that the S1 and S2 anchor rods on Pier E2 failed due to "short-term" HE (or IHE) and at the same time not hold the manufacturers accountable for the IHE failures is perplexing.

There is a more fundamental problem with the TBPOC conclusion that the S1 and S2 anchor rods failed on Pier E2 because of IHE (i.e., short-term HE according to the TBPOC).

2.7 Fundamental Problem with IHE as the Cause of the S1 and S2 Anchor Rod Failures

IHE as the cause of the S1 and S2 anchor rod failure has the following fundamental problem: IHE is inconsistent with all 32 failures occurring in the bottom threads while no failures occurred in the top threads.

IHE assumes that the anchor rods were charged with hydrogen above a threshold level during the anchor rod manufacturing processes such as during acid cleaning. Then, the hydrogen concentration would have to be uniform throughout the rods. The magnitude of a maximum stress in the bottom threads would be about the same as that in the top threads when the rods were pretensioned. If the hardness or strength of the anchor rods was about uniform, end to end, the susceptibility to HE would be about uniform also end to end. Then, the chance of IHE failures for the bottom threads would be about the same as the top threads, namely ½ or 0.5. Since the probability of IHE failure for each rod would be an independent event, the

[29] S. Brahimi, S. Rajagopalan, S. Yue, J. Szpunar: Effect Of Surface Processing Variables on Hydrogen Embrittlement of Steel Fasteners, Part 1: Hot Dip Galvanising, Canadian Metallurgical Quarterly, Vol. 48, No. 3, Sept. 2009 , pp. 293-301.
[30] S. Brahimi: Effect of Thermal Up-quenching on Internal Hydrogen Embrittlement of Hot Dip Galvanized High Strength Steel, to be presented at the 2014 TMS Annual Meeting and Exhibition, February 16 – 20, 2014, San Diego, CA.
[31] Reference 7, p.11.
[32] ibid, p. 76.

probability of the 32 anchor rods all failing in the bottom threads is less than one in four billion, as follows.

$$P(B) = (0.5)^{32} = 2.33\text{ E-10 or } < 1: 4,000,000,000$$

In other words, the probability of less than one in four billion would almost never happen and IHE cannot be the cause of the 32 anchor rods all failing in the bottom threads. Neither the ABC report nor the TBPOC report even mentioned this most significant and peculiar failure pattern of the S1 and S2 anchor rods: the 32 failures all occurred in the bottom threads and none of the top threads failed.

2.8 EHE (or *Long-term Stress Corrosion Cracking*) as the Cause of the S1 and S2 Anchor Rod Failures

The 32 anchor rod failures all in the bottom threads could occur if (1) the bottom threads experienced higher stress than the top threads consistently and (2) if the bottom threads were more susceptible to HE than the top threads consistently. Neither one is very probable, consistently for all 32 rods.

The only way to account for the fact that all of the failures were in the bottom threads is if they had a hydrogen concentration higher than the threshold level while the top threads did not.

As mentioned before, this was possible if the bottom threads experienced longer periods of wetness than the top threads. So, the hydrogen responsible for the 32 rod failures had to have been introduced into the steel after the rods were manufactured or while they were sitting in the grout cans (grout pipe, guide pipe, duct, or support cylinders) in the concrete cap beam of Pier E2 for some five years. This means that the hydrogen came from the environment and the 32 anchor rods failed due to EHE, which is the same as "*long-term stress corrosion cracking*" as used by the TBPOC.

Therefore, the ABC and the TBPOC reports both had a wrong conclusion as to the metallurgical cause of the S1 and S2 anchor rods on Pier E2 in March 2013. The 32 anchor rods for S1 and S2 Shear Keys failed due to EHE (or *long-term stress corrosion cracking*), not due to "*short-term hydrogen embrittlement*" or IHE.

2.9 Differences and Similarities between HE and SCC

According to Prof. Johnson of Cornell, there are essentially no differences, mechanistically, between IHE and EHE (or long-term SCC) as discussed earlier on page 6. His statements at the 1980 Symposium on Hydrogen Embrittlement are reproduced again below.[33]

> "Studies of water-induced cracking in high strength steels have shown that subcritical growth and delayed failure of high strength steels in water environment is caused by hydrogen, discharged from the water by the reaction with the steel."
>
> "Their experiments, (meaning Professor Troiano and his students,) removed the major objection to the concept that hydrogen is a causative factor in many examples of stress corrosion cracking.

[33] Reference 19.

Throughout their book, Fisher and his co-authors exclusively use hydrogen embrittlement or "hydrogen stress cracking" to mean internal hydrogen embrittlement (IHE) and stress corrosion or stress corrosion cracking to mean environmental hydrogen embrittlement (EHE) of high strength steels, as follows.[34]

> A490 bolts should not be galvanized since they become susceptible to stress corrosion cracking and hydrogen embrittlement.
>
> Although galvanizing does provide an excellent protection against corrosion of the bolt, it may increase its susceptibility to stress corrosion and hydrogen stress cracking. This applies especially to galvanized A490 bolts. Therefore, it was concluded that galvanized A490 bolts should not be used in structures.[4.23, 4.24]
>
> Hydrogen stress cracking as well as stress corrosion may cause delayed, "brittle" fractures of high-strength bolts. Although both processes have been studied extensively, no completely acceptable mechanism for explaining either phenomenon has been developed.
>
> For example, stress corrosion at least in part involves electrochemical dissolution of metal along active sites under the influence of tensile stress. Hydrogen stress cracking occurs as the result of a combination of hydrogen
>
> Since corrosion frequently is accompanied by the liberation of atomic hydrogen, hydrogen-stress cracking may occur in corrosive environments. However, in many situations a combination of both fracture patterns develops.
>
> From these test results, it became apparent that the higher the strength of the steel, the more sensitive the material becomes to both stress corrosion and hydrogen stress cracking.

Regarding HE and "*long-term stress corrosion cracking*," the TBPOC Chairman stated as follows during the July 10, 2013 BATA Oversight Briefing.

> What caused the bolts to fail and what might cause a longer term and related problem, called stress corrosion? What caused the bolt to fail is the phenomenon called hydrogen embrittlement. What we are worried about in the long term, the bolts that did not fail, is whether they might be at risk of *long term stress corrosion cracking*.
>
> You'll talk to some experts who might use these terms interchangeably and call them both a form of hydrogen assisted corrosion or cracking. We, in this review, I think, based upon the experts we consulted, tend to call them two different version of a similar phenomenon, the principal difference being that hydrogen embrittlement occurs in a very short time window, tends to be days or weeks after a steel item is put under tension, whereas stress corrosion cracking is really the subject of prolong exposure to stress, to tension, which lead to the occurrence.

What the TBPOC Chairman meant to say was of course that stress corrosion cracking is really the subject of prolong exposure of "steel under stress to corrosive environments," rather than "exposure to stress, to

[34] G. L.Kulak, J. W. Fisher, J. H. A. Struik: Guide to Design Criteria for Bolted and Riveted Joints, Second Edition, American Institute of Steel Construction (AISC), Inc., Chicago, IL, 2001, p.36, 66.

tension, …" In this case, the corrosive environments are moist marine air and aqueous environments. By using the time to failure as the principal criterion between HE and *long term SCC*, the TBPOC Chairman deviated from the convention (the source of hydrogen as the criterion), which is prevalent among most technical experts, including the ASTM.

The TBPOC Chairman apparently adopted Fisher and his co-authors' terminology, SCC for EHE, although somewhat outdated, and altered it by calling it "*long-term stress corrosion cracking*," which must have appealed to him for his own understanding of the differences between different nomenclatures of the same phenomenon, HE, which is confusing even to engineers. The term "long-term SCC" is, however, improper as discussed already, and more confusing to others, particularly to those outside the insular circle of state and federal agencies.

Fisher and his co-authors' concept about the involvement of "electrochemical dissolution of metal along active sites" (underlined in the above box for emphasis in this review) is true for SCC of steel such as intergranular stress corrosion cracking (IGSCC) of stainless steels but not for HE (IHE or EHE) of high strength steel. The only requirement for HE is the availability of hydrogen (i.e., the hydrogen concentration higher than a threshold level), the material being susceptible to HE, and the stress higher than a threshold level.

It is apparent that IHE does not have to involve corrosion at all because the hydrogen that can do the damage is already in the steel. All that is left to occur is a "crack initiation and growth," assisted by the hydrogen, which can occur in a "short time window."[35] This "crack initiation and growth" stage will be the same for EHE. What takes time for EHE and why it takes longer for EHE to manifest itself is that it must go through the stage of hydrogen accumulation in the steel.

HE, either IHE or EHE, does not have to involve the "electrochemical dissolution of metal along active sites." This is one of the main reasons why SCC or long-term SCC terminology is not preferable to EHE. The TBPOC and Caltrans, however, had and still have no materials engineers who could make this distinction or proper judgments on this and other materials engineering issues.

Eliaz et al cited the table below in characterizing the embrittlement mechanisms, HE, SCC, from a reference.[36,37]

Table 1
Comparison between typical characteristics of hydrogen embrittlement (HE) and stress-corrosion cracking (SCC) [1]

Characteristic	SCC	HE
Stress	Static tensile	Static tensile
Aqueous corrosive environment	Specific to the alloy	Any
Temperature increase	Accelerates	Increases to RT, then decreases
Pure metal	More resistant	Susceptible
Crack morphology	TG or IG branched sharp tip	TG or IG unbranched sharp tip
Corrosion products in the crack	Absent (usually)	Absent (usually)
Crack surface appearance	Cleavage-like	Cleavage-like
Cathodic polarization	Suppresses (usually)	Accelerates
Strain-rate increase	Decreases	Decreases
Near maximum strength level	Susceptible, but HE often predominates	Accelerates

35 Some cadmium plated high hardness fasteners (~50 HRC) can fail due to IHE in minutes of prestressing.
36 N. Eliaz, A. Shacha, B. Tal, D. Elieza: Characteristics of Hydrogen Embrittlement, Stress Corrosion Cracking, and Temper Martensite Embrittlement in High Strength Steels, Engineering Failure Analysis, 9 (2002), pp. 167-184.
37 D. A. Jones: Principles and Prevention of Corrosion, New York, MacMillan, 1992, pp. 234-89, 333-55.

Two of the main differences between SCC and HE above are the effect of cathodic protection (CP) and temperature. CP can suppress SCC while it "accelerates" or promotes HE. This aspect could pose a practical problem, for example for the tower base anchor rods. If the bottom ends of the 3 and 4 inch anchor rods in the tower foundation are electrically connected to a CP system (if any for the tower foundation) and if the anchor rod bottom ends could experience wetness for whatever causes, HE failures may be promoted in the bottom threads of those anchor rods. This concern has not been brought up so far, but should be addressed.

2.10 Lack of Materials Engineering Expertise by TBPOC-Caltrans and Their Contractors

The above discussions have established EHE, not "*short term HE,*" as the metallurgical cause of the S1 and S2 anchor rod failures. The root cause of these anchor rod failures is in the lack of materials engineering expertise by the TBPOC, Caltrans, and their contractors from the early design stage to the final construction stage of the SAS Bridge. The lack of understanding of various aspects of materials engineering resulted in poor decisions repeated throughout the project and reflected in the TBPOC's audacity or ignorance that allowed numerous errors in the TBPOC report when it was released. Several examples are discussed below.

(a) Lack of Distinction between Stress and Strength

The concept of stress vs. strength is very basic in both civil engineering and materials engineering. The distinction between stress and strength of a material is not difficult to understand.

Strength of a material such as ASTM A354 Grade BD is one of its properties, like hardness, ductility, and toughness that do not change (for a given temperature). Strength is usually uniform throughout a material. Conversely, stress in a material is not a fixed property; it can change from zero under no load to the breaking strength or tensile strength when overloaded to failure. Stress will increase or decrease as the load or force applied to the material increases or decreases. Also, stress can be higher or lower within the same material as affected by local conditions such as points of stress concentration, like threads. When an anchor rod is loaded or pretensioned, the stress in the threaded section would be higher than the smooth shank section whereas the strength would be the same in both sections.

The stress in an anchor rod would increase linearly in proportion to the applied load until it reaches a point where the anchor rod begins to "yield" or deform at a greater rate than under lower load. At this point, the stress in the material has reached a yield stress, which is usually referred to as the yield strength. Therefore, the term yield stress is not incorrect; but it is more commonly referred to as the yield strength except in special cases. The term yield stress could also mean any stresses that can cause a material to yield, namely any stresses between the yield strength and the tensile strength.[38] Thus, the term yield strength is preferred to the term yield stress in the context used in the TBPOC report. For example, "at stresses below the *yield stress* of susceptible materials" would be better understood if written "at stresses below the *yield strength* of susceptible materials."[39]

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[38] ASM Handbook, Volume 13A, Corrosion: fundamentals, Testing, and Protection, ASM International, Materials Park, OH 44073, p. 1072,

[39] Reference 9, p. 19 and 21.

The distinction between stress and strength for an anchor rod is much the same as in everyday conversations. For example, “she is under so much stress that she has no strength to stand up.” Her stress can vary; her personal strength is equal to the maximum stress she can sustain herself before she falls.

Nevertheless, the TBPOC report has mixed up stress and strength in five places (Table 1, items 5 and 13, Table 3, items 20, 48, and 129).

Also, during the July 10, 2013 BATA Briefing, in reference to the Venn diagram shown in Figure 11, the TBPOC Chairman stated as follows.[40]

> As you can see, there are three ingredients. … First is hydrogen. Second is high tensile strength, stress, or strength. And the third is material susceptibility. And that specially means hardness of material, especially at the surface of the material. …

The TBPOC Chairman just made an embarrassing error, a blooper. The Caltrans Director did, too, during BATA Briefings. Examples of their bloopers are discussed in Section 2.11 (page 25).

(b) Lack of Justification for Selecting ASTM A354 Grade BD over Grade BC

ASTM A354 has two grades: Grade BC and Grade BD. For anchor rods that are over 2½ inches in diameter, the minimum specified tensile strength is 115 ksi for Grade BC and 140 ksi for Grade BD. The specified hardness range is 22 – 33 HRC for Grade BC and 31 – 39 HRC for Grade BD, both for over 2½ inch in diameter. Being a lower strength material, Grade BC is not susceptible to HE (or SCC). So, if Grade BC had been selected instead of Grade BD, there would have been no S1 and S2 anchor rod failures on Pier E2 in March 2013. That is, Grade BC anchor rods for S1 and S2 would not have failed even when their bottom threads were exposed to pools of stagnant water for an extended period as happened to the Grade BD rods for Shear Keys S1 and S2 that failed.

The TBPOC report discusses why Grade BD had to be used, as follow.[41]

> **Why Were A354 Grade BD Steel Rods Selected for the SAS Bridge?**
>
> To make the strong connections, the designer selected A354 grade BD steel rods. The SAS Design Criteria, which were finalized on July 15, 2002, specify the use of ASTM A354 grade BD for a number of the structural steel connection locations.
>
> The highest-strength steel rods were required by the bridge design due to the low number of rod locations within the concrete pier cap at E2. At the east pier, if more rod locations were designed for, it would have required a larger upper and lower shear key and bearing base plate, which may have resulted in a larger pier cap and cross beam. These larger elements would have resulted in more mass, which would have affected the seismic forces that need to be accounted for in the design.

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40 http://www.mtc.ca.gov/news/current_topics/4-13/sfobb.htm

41 Reference 9, p.27.

In other words, the TBPOC is maintaining that Grade BC, being a lower strength material than Grade BD, would have required more rods, resulting in a "larger connecting surface" and a larger casting for shear keys. This could have potentially affected the entire seismic safety calculations, perhaps necessitating even a re-design of the cap beam of Pier E2. This would not be the case, however.

The shear key is a large steel casting (Figure 5a). It has a base plate that is roughly 9 ft square and 10.8 inches in thickness. The 48 anchor rods are spaced at 10 to 14 inches apart, centerline to centerline. Each rod has a spherical washer, which is 7 inches in diameter (Figure 5b). Thus, the shear key base plate can accommodate 3¼ inch diameter Grade BC rods as easily as 3 inch diameter Grade BD rods. No need to re-design the shear key base plate or the cap beam of Pier E2 would have been necessary. All that was required was to increase the rod hole diameter in the base plate by ¼ inch. The reason why this would have given the required clamping force equal to that of Grade BD rods is simple.

ASTM A354 requires minimum tensile strengths: 816.5 kips for 3¼ - 4UNC Grade BC and 835 kips for 3 – 4UNC Grade BD.[42] The former, 98% of the latter, would have been acceptable where the entire SAS Bridge has been "overdesigned to 140% of the worst of six different 1500 year return period earthquake time history generated loads," according to the Chief Bridge Designer of Caltrans.[43] Thus, the 3¼ - 4UNC Grade BC rods would have been acceptable. He stated further as follow.

> This can be read as there is a 40% extra capacity in the "as-designed" system at Pier E2 above the lifeline criteria that is above the national standard. In simple terms, the system at Pier E2 was not designed to the bare minimum and there was a significant reserve capacity incorporated into the design that we should recognize at this time as leaders consider opening day alternatives.

Therefore, the TBPOC report makes no strong case for why ASTM A354 Grade BD had to have been selected. The Designers selected Grade BD for shear key anchor rods without due deliberation regarding the dangers of HE (IHE and EHE) failures of hot dip galvanized Grade BD anchor rods.

As it turned out, the engineers at TY Lin and Caltrans were only concerned about IHE and were not cognizant of EHE (or SCC). They thought all they need to do to avoid HE was to specify dry grit blast cleaning in place of acid pickling to descale and clean the rod surfaces in preparation of hot dip galvanizing. The supplier complied with this requirement and the anchor rod failures were not due to IHE. Instead, their failures were due to EHE (or SCC) because the rods were susceptible to HE and they were not adequately protected from corrosion during the five year construction delay period.

[42] kip = kilo-pound = 1000 pound-force.

[43] Seismic Evaluation of SAS at E2 Pier prior to Completion of Shear Keys S1 and S2, July 13, 2013, TY Lin International/Moffat & Nichol Engineers, a Joint Venture, http://mtc.ca.gov/projects/bay_bridge/A354/Seismic_Evaluation_of_SAS-7-15-13.pdf

(c) Lack of Justification for Macalloy and Dywidag Threadbar as Anchor Rod Materials

Another reason why Grade BD material was chosen, according to the TBPOC report, was that it was difficult to procure proprietary materials, like Macalloy and Dywidag Threadbar.[44,45] These are high strength steel rods (150 ksi minimum tensile strength) that may be available only as a sole source.

The TBPOC report listed nine findings. Finding 3 is as follows.[46]

> 3. There was inadequate consideration to allow for sole-source specifications, utilizing alternative or specific mechanical properties of steel. In fact, proprietary Macalloy high-strength rods were specified for the pre-stressing rods in the W2 cap beam in the SAS special provisions. Investigation into other types of high-strength steel rods, even if they might have required-sole sourcing, appears to have been warranted.

The above Finding implies that if the proprietary rods had been allowed to be used as the shear key anchor rods, no failures would have occurred in March 2013. This Finding, however, is invalid as a finding because it lacks the necessary technical reasoning to support that Macalloy and other proprietary high strength steel rods could have avoided the EHE failures on Pier E2.

Macalloy would have been a good choice and should have been obtained in spite of it being a sole source material if it is immune to HE (or SCC) or at least more resistant to HE (or SCC) than Grade BD. Macalloy or its equivalents meet the requirements of ASTM A722.[47] They offer, however, no advantages over Grade BD in regards to the susceptibility to HE (or SCC).

The following data have been extracted from a Macalloy brochure.

> Macalloy bars were developed, initially, for use in prestressed concrete construction but have been adapted for many structural applications. Among these are: Anchor bolts for tension ties, Holding down bolts, etc.
>
> Macalloy 1030 is a carbon-chrome steel.[48] … All bars are hot rolled.
> Bars of 50 mm and 75 mm diameter are heat treated after rolling …
>
> For normal prestressed concrete construction, the alkaline environment, provided by a layer of cement grout, injected into the duct enclosing the bar gives good protection. If bars are used in exposed application, corrosion protection is essential for Macalloy 1030.
>
> **Macalloy 1030 should never be galvanised.**
>
> Macalloy 1030 bars have been subjected to the FIP standard stress corrosion test. No

[44] Macalloy, Sheffield S25 3QE, U.K. 1. www.macalloy.com
[45] http://www.dywidag-systems.com/
[46] Reference 9, p. ES-13, 25 – 28, 74
[47] ASTM A722 Standard Specification for Uncoated High-Strength Steel Bars for Prestressing Concrete. Minimum Tensile Strength required = 1,035 MPa (150 ksi).
[48] The "1030" refers to 1030 MPa (or 150 ksi) minimum tensile strength.

bars failed during the 200 hour duration of the test and subsequent tensile tests to failure showed no significant reduction in the ultimate or 0.1% proof stresses.

With a minimum tensile strength at 1030 MPa (or 150 ksi), Macalloy rods would be as susceptible to IHE/EHE (or SCC) as ASTM A354 Grade BD rods.

Dywidag Threadbar, is also "susceptible to stress corrosion cracking and hydrogen embrittlement in aggressive environments and, therefore, must be properly protected." [49]

Therefore, without proper protection from corrosion effects during construction (and during service), both Macalloy and Dywidag Threadbar would have failed just like the Grade BD anchor rods, had they been subjected to the same exposure to pools of stagnant water for an extended period as occurred to the failed Grade BD anchor rods. The sole source proprietary materials such as Macalloy and Dywidag Threadbar would not have been a solution.

The "FIP standard stress corrosion test" is most widely used in Europe for "for ascertaining the hydrogen embrittlement susceptibility of steels for prestressing concrete." [50] Ganz and Elices stated that "they [brittle failures of prestressing steels due to SCC] are often due to an accumulation of causes such as poor design, errors during construction, careless detailing and, in some cases, use of unsuitable material."[51] All of these high strength steel rods require proper protection from corrosion at all times to avoid EHE (or SCC) failures during construction and service. Macalloy or Dywidag Threadbar would have offered no advantages as an anchor rod material over ASTM A354 Grade BD.

Therefore, Finding 3 is without a rational understanding of the vulnerability of high strength steel to HE failures if they are not properly protected from corrosion whether it is proprietary or not.

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[49] DSI Info 20, http://www.dywidag-systems.com/

[50] M. Elices, L. Caballero, A. Valiente, J. Ruiz, and A. Martin:) Hydrogen Embrittlement of Steels for Prestressing Concrete: The FIP and DIBt Tests. Corrosion: February 2008, Vol. 64, No. 2, pp. 164-174.
doi: http://dx.doi.org/10.5006/1.3280685
FIP – federation internationale de la precontrainte (International Federation of Prestressing), merged with CEB – Comité Euro-International du Béton (the Euro-International Concrete Committee) to form The International Federation for Structural Concrete (fib – fédération internationale du béton) in 1998.
http://www.fib-international.org/about

> FIP Standard Test – most widely used.
> Immersion of prestressing steel in a solution ammonium thiocyanate (200g NH_4SCN + 800g H_2O)
> at 50ºC and stress the specimen to 80% of the tensile strength, time to rupture is measured:
> Extremely susceptible, 2 – 3 hours for cold-drawn wires,
> 10 – 15 hours Quenched and Tempered wires
> 30 – 50 hours for hot rolled bars.

[51] Hans R. Ganz and Manuel Elices: Influence of Material and Processing on Stress Corrosion Cracking of Prestressing Steel – Case Studies, FIB (CEB0-FIP) Technical Report Bulletin 26
Federation inertnationale du benton (fib), International Federation for Structural Concrete fib
2003 Switzerland fib@epfl.ch web: http://fib.epfl.ch IBSN 2-88394-066-5

(d) Lack of Understanding of ASTM A143 Hydrogen Embrittlement Test

Finding 8 of the TBPOC report is as follows.[52]

> 8. ASTM 143 required a hydrogen embrittlement test. The designer was aware of the potential of hydrogen embrittlement, but construction oversight technicians only tested rods with 1½-inch diameter or less. The large-diameter rods were not tested for hydrogen embrittlement and a Request for Information was not issued. Closer coordination was needed between design and construction staff.

The above finding implies that the shear key anchor rod failures could have been avoided if construction had performed the hydrogen embrittlement test of ASTM A143 for the 3 inch Grade BD anchor rods as well as for anchor "rods with 1½-inch diameter of less." This test would not have detected, however, the potential for IHE or EHE (or SCC) failures of the 3 inch shear key anchor rods as discussed below.

The "embrittlement test" procedure of ASTM A143 consists of bending specimens under monotonically rising loading and comparing the results of bending between specimens with hot dip galvanized and "black" specimens without hot dip galvanizing, as follows.[53]

> 9.2 A convenient bend test for embrittlement of galvanized steel hardware such as bolts, pole and tower steps, braces, rods, reinforcing bars, etc., consists of bending the article and comparing the degree of bending to that which is obtained on a similar ungalvanized article. The article, before and after galvanizing, may be clamped in a vise and using a lever if necessary, bent until cracking of the base steel occurs, or to 90° whichever is less.

The above test procedure may detect embrittlement due to strain aging, not due to IHE. This test procedure would be useless in assessing the susceptibility of anchor rods, regardless of the size, to EHE (or SCC), which was the cause of the shear key anchor rod failures.

Finding 8 of the TBPOC report indicates that TBPOC-Caltrans and their contractors do not understand the cracking mechanism of HE and the limitations of the embrittlement test of ASTM A143 from the specification preparation stage until now.

(e) Lack of Understanding of Effects of Heat Treatment

The TBPOC report adopted the conclusions of the ABC report, which stated: "The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement." As already discussed, this is unacceptable because the ABC report failed to define what the normal susceptibility of the steel is. Then, the microstructure being "inhomogeneous" and "less than ideal" and

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[52] Reference 9, p.75.

[53] ASTM A143 Standard Practice for Safeguarding Aging Embrittlement of Hot-dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement, Paragraph 9.2.

"low toughness and marginal ductility" are listed as primary factors that contributed to the failures.[54] Ductility as part of tensile properties has no significant effects on HE. This was already discussed in Sections 2.2 and 2.3. It will be discussed in Section 2.13 that toughness in terms of CVN (or KIc) values has little effect on HE (IHE or EHE).

Regarding the effects of heat treatment on anchor rod properties, the ABC report stated as follows.[55]

> There is a lack of uniformity in the microstructure which has resulted in regions of high hardness, which has a first order effect on HE susceptibility. Furthermore, the metallurgical structure and substructure of the steel, which are fundamentally a result of alloy selection and heat treatment conditions, has apparently made the rods less tough (i.e., more brittle) and therefore more susceptible to hydrogen embrittlement.

The TBPOC report listed the following factors as having contributed to the shear key anchor rod failures.[56]

- High Hardness — values greater than 35 HRC
- High Ultimate Strength — values 159–170 ksi (20% higher than minimum specified)
- High Tension Levels — 0.7 Fu
- Hot-Dip Galvanization
- Additional Heat Treatment
- An Embedded Rod Detail Exposed to the Environment

Regarding the effects of "additional heat treatment," the TBPOC stated as follows.[57]

> Also, when examined, the failed rods showed that the metallurgical structure was not uniform across the thickness of the rod and parts did not have the expected material properties. This indicates the steel production and heat treatment were not fully successful in achieving the desired uniform metallurgical structure and desired material properties.
>
> However, in this case, given what is now known about the poor quality of the 2008 rod material, the second heat treatment may have further hardened and strengthened the material and contributed to the rods' susceptibility to hydrogen embrittlement.

[54] Reference 9, p.20.
[55] Reference 7, p.2.
[56] Reference 9, p.20.
[57] ibid, p.ES-9, 43.

Also, when examined, the failed rods showed that the metallurgical structure was not uniform across the thickness of the rod and parts did not have the expected material properties. This indicates the steel production and heat treatment were not fully successful in achieving the desired uniform metallurgical structure and desired material properties.

The above statements reflect lack of understanding of what heat treatment can or cannot achieve with low alloy steels like 4140. The above statements in both the ABC and the TBPOC report are problematic for the following reasons.

(i) The TBPOC only speculated that the 2008 rods failed to achieve a "desired uniform metallurgical structure and desired material properties" because "the steel production and heat treatment were not fully successful."

As discussed already, a 3 inch 4140 steel round cannot achieve a uniform metallurgical structure across the entire cross section because its mass and chemical composition are not amenable for through-hardening. If the heat treatment were done improperly and were to be blamed for the anchor rod failures, the ABC team should have done a heat treatment experiment to prove the point. If indeed the [bad] heat treatment contributed to the failure, the anchor rod supplier should have been held accountable. The ABC team was not diligent in providing the evidence to support its suppositions.

(ii) The second heat treatment or an additional heat treatment cannot "further harden" and strengthen the material any more than the first heat treatment that was done properly. If the first heat treatment was not done properly, for example, if the rod metal temperature did not reach the autenitizing temperature (e.g., 1600ºF) throughout the cross section before quenching in an oil bath or the cooling was interrupted or slow for whatever reason, the as-quenched hardness may have been too low. If this was the cause of the second heat treatment and it was done properly, the rod would have attained the right microstructure and hardness appropriate for the final tempering temperature used. The second austenitizing treatment should have wiped out any previous heat treatment hysteresis and could not have "further hardened and strengthened the material."

Therefore, the additional or a second heat treatment and lack of uniformity in microstructure may not be cited as factors that contributed to the anchor rod failures.

(f) Lack of Proper Sampling for Metallurgical Failure Analysis

Figure 1b shows that Shear Keys S1 and S2 each had two sets of anchor rods, 30 L1, each 17 ft long, and 18 L2, each 10 ft long. The 60 L1 anchor rods for S1 and S2 came from HT #644914 and the 36 L2 anchor rods for S1 and S2 from HT #644912. Out of 60 L1, 27 failed, or a 45% failure rate for L1. Out of 36 L2, 5 failed, or a 14% failure rate. Also, Shear Keys S1 had a failure rate 44% (21 out of 48) and S2 a failure rate of 23% (11 out of 48).

In spite of the significant differences in failure rates between the two heats (or L1 and L2), the ABC team evaluated only two samples from L1, one each from S1 and S2, and none from L2. It was improper to brand the entire 2008 rods (L1 and L2) as coming from a bad batch when no samples from L2 were evaluated for a failure analysis.

Chung previously pointed out that some laboratory data in the ABC report need to be validated. For example, the data shown in Figure 9 (left) may have resulted from a specimen that was improperly prepared for hardness testing.[58] Specifically, the skewed hardness profile and the uneven appearance of the specimen surface may indicate that improper surface grinding of the specimen could have affected the hardness of the localized area. In spite of the potentially erroneous hardness data, the Caltrans Director used this particular hardness plot in Figure 9 (left) as one of significant findings.

Also, the ABC team did not evaluate the zinc coating of the threads that failed or the top threads for comparison purposes. As Townsend noted, the ABC team should have determined if the white deposits on the threads near the fracture were corrosion products or grout.[59]

2.11 Caltrans and TBPOC Bloopers

Since March 27, 2013 when Caltrans first announced the S1 and S2 anchor rod failures on Pier E2, the TBPOC and Caltrans gave several briefings to BATA commissioners and to the public.[60] There were several "bloopers" during the presentations. These several "bloopers" during the presentations and in their reports are indicative of lack of expertise in materials science (metallurgy) and materials engineering. Two of them are discussed below as exemplars.

(a) Caltrans Director's Bloopers

The SAS Bridge has 2,306 HDG ASTM A354 Grade BD anchor rods as shown in Table 1 of the TBPOC report.[61] This table along with a photograph of the SAS Bridge with anchor rod locations is reproduced in Figure 2. Pier E2 has 832 Grade BD anchor rods (Item No. 1 – 4). Of these, 96 (Item 1 for Shear Keys S1 and S2 base plate anchor rods) were purchased and installed in 2008 on Pier E2 because of their locations being directly above the pier columns and they had to be embedded in the concrete cap beam. The rest (736) were among those purchased in 2010 and installed sometime in 2012 and 2013. The TBPOC likes to refer to the 96 anchor rods for S1 and S2 base plates as the "2008 rods" and the rest of the 736 rods on Pier E2 and some other rods as the "2010 rods." This was apparently based on their desire to instill the idea that only the "2008 rods" were of "low quality steel." For example, the TBPOC report stated as follows:[62]

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[58] Y. Chung: Comments on Caltrans' Metallurgical Report on Pier E2 Anchor Rod Failures, p.12, http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_D_Correspondence/D7_Report_and_Letter_from_Yun_Chung.pdf

[59] C.3 6/7/2013 A354 Bolts Testing and Evaluation Meeting Material, http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_C_Other_Meetings/C3_A354BD_Bolts_Testing_and_Evaluation_Meeting.pdf

[60] BATA: Bay Area Toll Authority. BATA manages and invests revenues from all tolls levied on the seven state-owned toll bridges: Antioch, Benicia-Martinez, Carquinez, Dumbarton, Richmond-San Rafael, San Francisco-Oakland Bay and San Mateo-Hayward. http://bata.mtc.ca.gov/

[61] Reference 9, p. 6

[62] ibid, p. 66

short-term hydrogen embrittlement is isolated to the shear key S1 and S2 anchor rods at the top of Pier E2 manufactured in 2008.

At almost every briefing to the BATA Oversight Committee, the TBPOC emphasized the above idea that the "2008 rods" came from a bad batch of steel and the "2010 rods" from good batches of steel. This was most evident during the July 10, 2013 BATA briefing. The Caltrans Director presented the fracture faces of a "Failed 2008 Rod" and a [typical] "Other Rod." This slide is reproduced in Figure 12. His statement during the briefing in reference to these fracture faces has been transcribed as follows:[63]

> "… This is a significant finding. All the 2008 bolts that fractured, the 32 out of 96, at E2, had a brittle failure. All the other bolts that we tested, both in the lab and in the field, uhh, not in the field, in the lab, in samples as well as in full size, ah, had a ductile failure. And that is a good thing; a brittle failure is a bad thing. …"

The only good part of the above statement is the last sentence. The rest is bad because it only reveals his and his staff's ignorance about metal fractures and about why some rods fracture in a brittle manner while others in a ductile manner. They would not understand even a mild steel that would fracture in a ductile manner, for example with 30% or more elongation in a standard tensile test using a round cross section, could fracture in a brittle manner in the presence of a notch, like a pre-existing crack such as an HE crack in the "Failed 2008 Rod in Figure 12 (left).

It may very well be true that "all the 2008 bolts that fractured, the 32 out of 96 at E2, had a brittle failure." Caltrans' contractor removed, however, nine broken rods for examination from S1 and S2 base plates (Figure 1b). So, the Caltrans Director should not have said all had a brittle failure as if they had examined all 32 fractures.

It is significant to recognize that what Caltrans' Director said, "a significant finding," is significantly wrong, because

(1) Comparing a field failure due to HE with a lab tensile test failure is wrong; it is worse than comparing an apple to an orange. These fractures occurred under entirely different loading conditions.

(2) The failed 2008 rod showed a brittle fracture more because of the notch effect of a pre-existing crack (or the hydrogen embrittlement crack, marked a_c in Figure 12 (left), that initiated along the thread root, marked by arrows H1-H2-H3, and grew gradually over several days), than because the steel had a poor microstructure, marginal ductility, or low toughness.

The smooth appearing HE crack zone, looking like a C in reverse, marked by arrows H1-H2-H3, encompassed about 60% of the thread root circumference. The tip of this crack at arrows H4-H5-H6 acted as a sharp notch that triggered the final fracture, ff, when the remaining intact cross section, marked ff, could not sustain the static stress in the rod. The effect of a notch on creating brittle fractures, particularly in thickness greater than about ½-inch in steels, is common knowledge among materials engineers. The notch effect of a single HE crack as a "stress intensifier" (Figure 12 (left)) is far greater than a series of thread roots during a lab tensile test in Figure 12 (right).

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[63] http://www.mtc.ca.gov/news/current_topics/4-13/sfobb.htm , Video, BATA Presentation, 7-10-2013, 41' 38".

Conversely, the fracture face of the “Other Rod” that was labeled a “Ductile Failure in Lab Test” was produced under a monotonically rising load, in a matter of several minutes. About ¾ of this fracture, marked “1” and “2,” is macroscopically brittle, which is surrounded by shear lips, marked “3,” which are considered shear or ductile fractures, roughly at 45º with respect to the rod axis. So, the fracture face labeled “Ductile Failure in Lab Test” in Figure 12 consists roughly of 75% brittle fracture (1 and 2) and 25% ductile fracture (3), macroscopically. The difference in the fracture appearances in Figure 12 is really not a “big deal” at all or “significant” to talk about at a presentation.

(3) If a“2008 rod” without the HE crack was broken in a lab tensile test under a monotonically rising load as was done for the “other rod,” the former would have fractured just like that of the “Other Rod” in Figure 12 (right). Only the size of the shear lips could vary, depending on the ductility; but basically will be not much different.

(4) Conversely, if one of the “Other Rods” had failed due to hydrogen embrittlement (IHE or EHE), the fracture face would have looked like that of the “Failed 2008 Rod” in Figure 12 (left). Only the size of the smooth fracture zone (or the HE zone along the thread root at arrows H1-H2-H3) could vary depending on the toughness of the steel and stress; but basically will be not much different.

(5) If the three upward yellow arrows from “2” to “3” and the two downward yellow arrows from “3” in the fracture face of the “Other Rod” in Figure 12 (right) were meant to indicate the fracture propagation directions, the top two yellow arrows from “3” are wrong. The shear lip at “3” would not propagate as indicated by the top two yellow arrows. No shear lips in tensile specimen fracture faces will propagate as indicated by the two top yellow arrows. The top two yellow arrows from “3” would indicate that the shear lip fracture at the top of the picture originated at “3” and propagated across “sharp steps,” forming a jog and propagated downward. This will not happen and the yellow arrows from “3” are wrong.

Instead, the white arrows in Figure 13a indicate probable fracture propagation directions in the shear lips, including that for the shear lip at “3.” The black arrows point to a narrow flat fracture band along the thread root that intersected the shear lips. Figure 13b shows a perspective view of the same fracture face as that in Figures 12 (right) and 13a. Figure 13b is from File E17.[64] Figures 13a and 13b clearly show why “3” could not have acted as a fracture origin for the shear lip and the shear fracture could not have propagated toward “5” across the sharp step. The same is true for the left yellow arrow from “3.”

Figures 14a and 14b show a 2 inch and a 3-inch diameter ASTM A354 Grade BD anchor rods, respectively. They were tensile tested in full size by Caltrans.[65] Again, the top two yellow arrows were marked incorrectly as crack propagation direction indicators. In addition, the long upward yellow arrow along the diameter in Figure 14a does not really do the job because the fracture propagation directions in this region are quite complex as indicated by various valleys and ridges in the top two-thirds of the fracture face. A fracture path will not be continuous across ridges or valleys.

Figures 14c is a scanning electron fractograph from area “1” in Figure 14b. Macroscopically, the fracture face at “1” is brittle in Figure 14b; it is flat and without signs of plastic deformation such as stretching,

[64] File E17: SAS A354 Testing Program Results, Tests I, II & III.
http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_E_Rod_Project_Binders/E17.pdf
[65] ibid.

elongating, or distorting. Microscopically, however, the area "1" in Figure 14b consists entirely of dimpled fractures, which are a ductile fracture mode microscopically, as shown in Figure 14c. The "large" holes in Figure 14c form usually around nonmetallic inclusions, or some other second phase particles, such as those marked by the yellow arrows. They are seldom referred to as a "cup and cone," as used in the caption of this and other fractographs in File E17. Firstly, they are all "cups" without "cones." Secondly, the "cup and cone" description applies to the macroscopic appearance of ductile fractures with shear lips of machined round tensile test specimens and not to the holes (or "cups') in scanning electron fractographs of dimpled fractures under high magnifications.

The scanning electron fractograph in Figure 14d from area "2" in Figure 14b consists of about 50:50 dimpled and cleavage fractures. Although area "2" is macroscopically brittle, it is not entirely brittle microscopically. Thus, what is brittle and what is ductile is sometimes difficult to define. A distinction between them may be unclear whether in terms of a microscopic scale or a macroscopic scale. It may even be meaningless as used in the "Mode of Fracture" in Table 13 of the TBPOC report,[66] to be discussed in 2.16.

One more fracture face of a full size tensile test is shown in Figure 15a, just to illustrate that the wrong arrows in Figures 12, 13 and 14 are not a fluke. Caltrans lab engineers consistently erred in fracture face interpretation.

A correct determination of fracture characteristics including the directions of crack propagation is prerequisite to understanding and determining the cause of metal fractures. It is one of very basic materials laboratory skills required for any engineers charged with tensile testing of steel specimens and examining fractured metal parts. The Caltrans engineers who prepared File E17 had little knowledge about metal fractures. This will be elaborated more in Section 2.16 of this report.

The problem is not just that these simple errors were made in fracture face interpretation. The problem is why Caltrans thought these scanning electron fractographic evaluations of tensile test specimens were even necessary or why Caltrans testing protocols required three chemical composition determinations on a cross section of 2 inch or 3 inch diameter rods. The scanning electron fractography of the tensile specimen fracture faces was unnecessary and one chemical composition determination would have been sufficient for 2 inch or 3 inch diameter rods.

The problem is that the Caltrans organization has no one who could have caught such errors of overdoing a job for no good reason as those discussed above or could have corrected "significant" errors before the Caltrans Director presented Figure 12 as "a significant finding" to the world without realizing he was making a blooper.[67] This is a management problem as discussed in 4.0, Failure of Caltrans Director as Engineering-Construction Project Manager.

(b) TBPOC Chairman's Bloopers

The TBPOC Chairman made the same point about the brittle fracture of "the 2008 rod" as opposed to the "ductile fracture" of "the 2010 rod." In Figure 16, the slide he used to make this assertion during the May

[66] Reference 9, p.70.
[67] The caption of the scanning electron fractograph, reproduced in Figure 14c, was also wrong.

8, 2013 BATA Briefing is reproduced.[68] Referring to Figure 16, The TBPOC Chairman stated in part as follows.[69]

> That little break at the bottom, if you can see that circle there, if you remember the break that occurred on the 2008 bolts, from a prior presentation, it was a brittle break, and it was fairly clean. You see here that this break is much…I won't say dirty, because that's the opposite of clean, but it…what it reveals is something that pulls apart and is more ductile, more flexible, which is what you would like to see in this test so that it's not as brittle, not as hard.

Obviously, the Caltrans Director elaborated more of the same misunderstanding on the relationship between ductility and HE. Both of them and their engineers did not understand that the ductility displayed in laboratory tensile tests, either in full size specimens or machined specimens, is irrelevant to the material's susceptibility to HE (IHE, EHE, or both). This same misunderstanding about the brittle HE failures vs ductile lab tensile fractures lasted for more than two months and may still be prevalent among Caltrans engineers.

In the keynote speech at the 1980 Symposium on Hydrogen Embrittlement and Stress Corrosion Cracking, Professor Johnson also stated as follow:[70]

> "Delayed failures in high strength steels [due to HE] often occur under circumstances where tensile and bend tests showed no evidence of brittleness."

The TBPOC Chairman, the Caltrans Director, and their engineers displayed little understanding of metal fractures as discussed above. They could not understand how a ductile material can break in a brittle manner. This is, however, how ductile steels behave when they fracture in the presence of a notch. The fracture appearance is influenced drastically by the presence of a notch (or a crack tip), strain rates, and temperature.

To understand this "mystery," the science of fracture mechanics was developed in the 1960 – 1980's, which added new jargon, stress intensity factor, K, and critical stress intensity factor, KIc, often shortened as stress intensity and critical stress intensity, respectively. The latter nomenclature is incorrect; they are often accepted, however, as equal to the former. [Linear] fracture mechanics can explain what happens to the stress state in the material ahead of the tip of a crack that ordinary mechanics cannot.

Figure 17 is one of the slides that the TBPOC Chairman presented at the May 8, 2013 BATA Briefing.[71] The graph he presented was supposed to mean that the critical stress intensity factor for stress corrosion cracking, KI_{SCC}, along the ordinate (the vertical axis), decreases with hardness along the abscissa (the horizontal axis). TBPOC engineers mislabeled the graph in Figure 17 as "Sample Critical Stress Curve from …," indicating lack of expertise in fracture mechanics related terminology. The critical stress

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[68] http://www.mtc.ca.gov/news/current_topics/4-13/sfobb.htm , Video: BATA Oversight Presentation, 5-8-13. http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2047/7_E2_Anchor_Rods_for_BATA_May_8_2013_Final.pdf
[69] http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_A_BATA_Meetings/A-4_BATA_Meeting_May_8_2013.pdf
[70] Reference 19.
[71] http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_A_BATA_Meetings/A-4_BATA_Meeting_May_8_2013.pdf, slide 25.

intensity (or more correctly, the critical stress intensity factor) is related to, but not the same as, the critical stress. Therefore, it would be erroneous to label this graphs as a "Sample Critical Stress Curve …"

The TBPOC Chairman borrowed this graph in Figure 17 from the only technical reference in the TBPOC report, as follows:[72]

> Therefore, it has been necessary to establish which rods are at risk for stress corrosion cracking and to perform additional analytical testing — using as a guide the published research of John.W. Fisher[12] and H.E. Townsend[13]. Fisher published a book entitled, *Guide to Design Criteria for Bolted and Riveted Joints, 2nd Edition,* Kulak, G.L., Fisher, J.W., Struik, J.H.A. in 1987. His research found that electroplated and hot-dipped zinc coatings decrease the resistance to stress corrosion cracking in direct levels of stress intensities. Stress intensity is a function of the diameter of the rod and the tension the rod is placed under.
>
> the higher the stress, the rod will have higher stress intensity. The other key factor in stress corrosion cracking is the hardness of the steel, especially at the surface of the material.

In the above paragraph, "His research" would refer incorrectly to Fisher, not to Townsend. The warning statement about "hydrogen stress cracking or stress cracking corrosion" of "hot dip galvanized Grade BD bolts" in Note 4 of ASTM A354 is based on Townsend's research paper in 1975, not on any "researches" done by Fisher on corrosion or stress corrosion cracking. Professor Fisher's expertise lies in civil engineering, not in materials science or corrosion science.

The graph in Figure 17 has open triangles and open squares along the lower-right part of the curve. These are denoted by solid triangles and solid squares in the notation below the graph. This error (inconsistency) occurred when Fisher and his co-authors "borrowed" the graph from the Townsend's original paper and the TBPOC blindly copied the graph with errors in it from the book by Kulak et al.[73] Then, the TBPOC Chairman said, referring to this graph in Figure 17, that the larger the rod diameter, the lower the stress intensity factor for SCC. This graph has no data on the rod size; he would have needed another graph to make his point about the effects of rod sizes.

The above book by Fisher and his co-authors also has an error shown below.[74]

> Hydrogen stress cracking occurs as the result of a combination of hydrogen in the metal lattice and tensile stress. The hydrogen produces a hard martensite structure that is susceptible to cracking.

The statement highlighted above, "The hydrogen produces a hard martensite structure that is susceptible to cracking," must be a misstatement. Hydrogen may influence the formation of strain induced martensite in austenitic stainless steels, like Type 304L. There is no metallurgical literature that would support that "hydrogen produces a hard martensite structure" in carbon and low alloy steels, the main structural materials in civil engineering. Martensite in low alloy steels is hard, with or without hydrogen. Hydrogen does not promote the formation of martensite in low alloy steels, like 4140.

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[72] Reference 34, pp. 57-58.
[73] ibid, p.69.
[74] ibid, p. 66.

2.12 Misunderstanding and Misrepresentation of Wet Test (or Townsend Test)

During the May 8, 2013 BATA Briefing, the TBPOC Chairman made the following statement in reference to the graph in Figure 17.[75]

> For long-term stress corrosion, you're trying to simulate something that occurs over years or decades, and that's considerably more difficult. So we have come up with a…a…really a custom test that is going to try to simulate that longer term susceptibility to stress corrosion.

This was the beginning of misunderstanding of the SCC test designed by Townsend. From a description of his test and the reference that the TBPOC Chairman made to the graph in Figure 17, the objective of the Townsend test (or the wet test by the TBPOC Chairman) is to determine the critical stress intensity factors (or the critical stress) for stress corrosion cracking, KI_{SCC} (or σ_{SCC}), using full size sample rods as specimens, perhaps for different hardness levels. Ultimately, the KI_{SCC} data may be used to determine the threshold stress level below which HE would not occur for a given hardness/strength level irrespective of a hydrogen concentration in the steel.

Problems arise when the Townsend Test is misrepresented as a test to determine "long-term stress corrosion susceptibility" as in Figures 17 and 18. The KI_{SCC} test has no ability to predict a "longer-term" performance of a rod in a given environment such as the San Francisco-Oakland Bay. Therefore, the caption of the graph in Figure 17 or the definition given by the TBPOC, shown below, is incorrect.[76]

> **Townsend Test** An accelerated test to determine the longer-term susceptibility of a material to stress corrosion cracking. The material being tested is soaked in a controlled, concentrated salt solution while tensioned progressively over a number of days until failure.

The Townsend Test is not what the following statement by a Caltrans engineer made to reporters: "The corrosion testing is to see how the material will perform in a marine environment, over decades and under tension."[77] Other Caltrans engineers said the same thing at different times to reporters. This is a misrepresentation or at least "too much of a stretch" of the Townsend Test.

[75] Reference 69.
[76] Reference 9, p.93.
[77] Caltrans Performing Stress Tests On Bay Bridge Rods, August 2, 2013, http://sanfrancisco.cbslocal.com/2013/08/02/caltrans-performing-stress-tests-on-bay-bridge-rods/

The "SFGate.com" had the following comments by Russell Kane on the Townsend Test.[78,79]

> **Caltrans' tests questioned**
>
> "It's really hard and requires of lot of thought and luck to re-create the field situation in a laboratory - I have spent 30 years doing it," said Russ Kane, a hydrogen-assisted cracking and corrosion expert in Texas.
>
> "Sometimes you can't get it to fail, no matter what you do," Kane said. "You have to know all the variables. In complex, engineered structures, it's impossible to know all the variables."

This is why the Townsend Test is not what the TBPOC wants the public to believe. It cannot solve all the problems associated with "*long-term stress corrosion cracking*" of anchor rods on the SAS Bridge. It will only determine either KI_{SCC} or σ_{SCC} for the particular specimens being tested. The data may be useful in determining a threshold stress for avoiding SCC (or EHE) in conjunction with other data. The Townsend Test is not a test that can directly "determine the long term susceptibility of the material to stress corrosion [cracking]." Also, the KI_{SCC} data may not be used to predict if or when a rod may fail due to SCC (or EHE) during service.

2.13 Effects of Toughness on HE Susceptibility and HE Failures

In both the ABC and the TBPOC reports, toughness of the steel looms large as an important factor that affects the susceptibility of high strength steel anchor rods to HE. The CVN values obtained from the failed anchor rods of S1 Shear Key (e.g., 13.5 ft-lbs at 40ºF from S1G1) were touted as one of key factors that contributed to their failures. For example, Conclusion 3 of the ABC report is as follows.[80]

> 3. The metallurgical condition of the steel was found to be less than ideal. More precisely, the microstructure of the steel is inhomogeneous resulting in large difference in hardness from center to edge, and high local hardness near the surface. As an additional consequence of the metallurgical condition, the material exhibits low toughness and marginal ductility. The combination of all of these factors have caused the anchor rods to be susceptible to HE failure.

To support the above conclusion, the ABC report stated as follows.

> in hardness from center to edge, indicating that the steel may not have had optimal through-thickness hardenability or that it was improperly heat treated. The rod material also lacked toughness, with low Charpy Impact values ranging from 13.5 to 17.7 ft-lb.

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78 Bay Bridge fasteners withstand tests, Caltrans says
Jaxon Van Derbeken, Updated 10:48 pm, Sunday, August 25, 2013
http://www.sfgate.com/bayarea/article/Bay-Bridge-fasteners-withstand-tests-Caltrans-4760330.php

79 Dr. Russell Kane is "a recognized expert on materials selection for prevention of corrosion, hydrogen embrittlement and stress corrosion cracking …" "He developed detailed temperature, strength (hardness), and H2S concentration guidelines for the use of high strength steels in H2S service." http://www.icorr.net/?p=5

80 Reference 9, p.ES-6, ES-10.

The CVN values cited above came from 13.5 ft-lbs at 40ºF for S1G1 and 17.7 ft-lbs at 70ºF for S2A6, both as an average of a set of three tests. The CVN specimens were machined from the rod surface layer as close to the circumferential surface as possible with a notch located as close to and parallel to the surface as possible.

The stock material, 3 inch round 4140 steel, to make the S1 and S2 anchor rods does not have high hardenability as compared with, for example, 4340. This is well known (Figure 19), at least among materials engineers. Whether the rod was improperly heat treated or not could have been verified by conducting a heat treatment experiment, which was not done. Then, the ABC and the TBPOC reports cited 13.5 to 17.7 ft-lbs CVN (Charpy V notch) impact values as low toughness that was a significant factor in the HE failures of the S1 and S2 anchor rods, based more on the authors' opinion than technical justifications. They offered no technical references to back up their opinion on the effects of toughness on HE failures. Their interpretation of the low CVN values, however, had an important impact on the remedial decision by the TBPOC and has affected almost every decision TBPOC/Caltrans have made with regards to the disposition of the entire Grade BD rods on the SAS Bridge.

There is, however, no metallurgical evidence that notch toughness affects HE susceptibility in any significant way. Notch toughness may be one of many metallurgical factors that could interact with each other, including the effects of tramp elements such as tin or phosphorus on metal embrittlement. Notch toughness in terms of CVN or KI_C does not stand out as having an important effect on HE among the many metallurgical factors that may have some mutual effects on each other.

The technical literature on HE and SCC provides little data regarding the effects of toughness on HE crack initiation. What is known is that HE failures have occurred in high strength materials with high toughness such as Aermet 100, as shown below.[81]

> Near-peak-aged AERMET 100 is susceptible to severe internal hydrogen embrittlement (IHE) at 23 °C, if a sufficient diffusible hydrogen content is present, compromising the high toughness of this ultrahigh-strength steel (UHSS). Evidence includes the threshold stress intensity for subcritical IHE (K_{TH}) as low as 10 pct of the plane-strain fracture toughness (K_{IC}) and a fracture-mode transition from microvoid coalescence to brittle transgranular (TG) cracking, apparently along martensite lath interfaces and cleavage planes. The K_{TH} value decreases from a K_{IC} value of 132 to 143 MPa$\sqrt{m}$ to 12 MPa$\sqrt{m}$, and the amount of brittle TG fracture increases to nearly 100 pct as the concentration of diffusible H increases from essentially 0 to 8 wppm, with severe embrittlement in the 0 to 2 wppm

In the above quotation, KIc of 132 MPa√m is equivalent to 120 ksi√in or to about 40 ft-lbs CVN energy absorption. It seems at present not probable to make high strength steel immune to HE by improving notch toughness any more than toughness cannot improve resistance to fatigue cracking. Another well-

[81] R. L. S. Thomas, J. R. Scully, R. P. Gangloff: Internal Hydrogen Embrittlement of Ultrahigh-Strength Aermet 100 Steel, Metallurgical and Materials Transactions A, Vol. 34A, Feb. 2003, pp. 327-344.

Table I. Chemical Composition of AERMET 100 (Weight Percent)

Fe	Co	Ni	Cr	Mo	C	Ti	P	S	H (wppm)	
Bal	13.43	11.08	3.00	1.18	0.23	0.009	0.003	0.0008	0.26	0.35*

Table II. Mechanical Properties of AERMET 100

HRC	σ_{YS} (MPa)	σ_{UTS} (MPa)	RA (Pct)	Strain-Hardening Exponent* (1/*n*)	*E* (GPa)	σ_o (MPa)	K_{IIC}** (MPa$\sqrt{m}$)	
54	1765	1985	61	0.03	194.4	1985	132	143 (LR) 127 (CR)

1765 MPa and 1985 MPa are equivalent to 260 ksi and 290 ksi, respectively.

known example to consider is the chloride stress corrosion cracking of Type 304/304L stainless steel. It may have about 240 ft-lbs CVN toughness at room temperature. Yet, this grade of stainless steel is vulnerable to SCC as demonstrated by many service failure reports.

Another point to consider as to why toughness has little effects of HE is that the CVN specimens of 4140 steel, heat treated to meet the Grade BD tensile requirements, will have transgranular fractures at 40ºF or 70ºF. HE crack initiation and growth in high strength steel anchor rods will be almost always intergranular. This may be another reason why CVN toughness or KIc toughness has little effects on IHE or EHE failures.

In an email inquiry about the effect of toughness on SCC [or HE], Professor Pense of Lehigh University stated as follows:[82]

> "It is my opinion that fracture toughness, as measured by KIc or by Charpy testing, is not directly related to stress corrosion cracking [or EHE], but because most large high strength bolts, as well as most structural fasteners, will have some residual micro-cracks or sharp discontinuities from processing and adequate fracture toughness as measured but the CVN test is a necessary requirement. However, that alone will not protect high strength bolts from stress corrosion cracking [or EHE]."

Therefore, low CVN values of 13.5 ft-lbs from one of the failed shear key anchor rods may not be used as a valid reason that it failed because of low toughness.

Regarding the effects of CVN toughness, Professor Fisher stated as follows.[83]

> "… If 50 ft-lbs can be obtained, then I see no reason not to have it. It will allow a much larger crack before instability develops and this has to result in a better quality product. If you consider the long term performance particularly if galvanized products are going to be used, I think this will drive the ultimate strength (and HRC) down toward their lower limits. We know from A325 bolts that have a upper limit of 34HRC, that we have never had a problem with SCC or HC even when galvanized. If A354BD bolts and rods are going to be used and galvanized, then they are more likely to perform with these more stringent requirements. …"

There are several issues with the above opinion. A325 bolts are limited to 1½ inch in diameter. The 3 inch or 4 inch diameter ASTM A354 Grade BD rods for the SAS Bridge have metallurgical problems of their own just because of the large size that the small bolts of A325 do not have.

If the main benefit of high CVN values like 50 ft-lbs at 40ºF is to "buy" more time rather than to improve or lower the HE susceptibility, it is not worth the trouble for requiring and conducting the CVN tests as part of production quality control tests and acceptance verification tests. The reasons are very simple.

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[82] Private Communication with Prof. Pense, July 15, 2013.
Dr. Alan W. Pense has previously served as Chair of the Department of Materials Science and Engineering and Dean of the College of Engineering and Applied Science at Lehigh University. He specializes in physical and mechanical metallurgy.

[83] Private Communication, July 15, 2013. John Fisher,
Prof. John Fisher is a member of the Toll Bridge Seismic Safety Peer Review Panel for Caltrans/TBPOC. For Fisher's credentials, see Reference 9, p.86.

Referring to Figure 12 (left), Caltrans testing protocols call for a CVN test specimen location at C1, from the surface layer as close to the rod surface as possible. What controls the critical crack size, a_c, in Figure 12 (left) would be the toughness at C2, at the end of the HE crack zone that initiated at a thread root and has grown over a period of several days after the rod was pretensioned. Since a 3 inch 4140 steel rod will have a bowl shaped hardness curve across the diameter, like Figure 10, when quenched and tempered in accordance with the heat treatment requirement of ASTM A354, Grade BD, C2 will have different CVN values from those at C1. Therefore, the CVN values at C1 as a rod production control or a procurement specification requirement would be useless in "buying" the time once microscopic HE cracks have formed at a thread root. Also, it would be futile to specify other locations than C1 for CVN testing for the same purpose.

If the a_c in Figure 12 (left) reached about R/2 (mid-radius) in less than two weeks after the rod was pretensioned, it would have taken only another two weeks or so for this crack to advance to D/2 (center), at which point what CVN values might have been specified for the surface layer would have made no difference. So, the difference between a low toughness rod and a high toughness rod would be only a matter of weeks of the "time to failure" after pretensioning. That is not of much benefit.

Therefore, a CVN test requirement would not make the ASTM A354 Grade BD rods more resistant to HE failures and is not worth the trouble of specifying as a supplementary requirement for new replacement rods.

2.14 TBPOC's Rod-by-Rod Resolution

According to Table ES-2 and Table 14 of the TBPOC report, Items 2 - 4 and Item 11, shown below, will be replaced with new rods to be purchased with new supplementary requirements.[84] See Figure 20 for these items.

Item No	Rod Names	Qty	Dia inch	Length ft
2	Base plate anchor rods Shear keys S3 and S4; Bearings B1 – B4	192	3	22 - 23
3	Top rods, Shear keys S1 – S4	320	3	2 – 4.5
4	Top rods, Bearings B1 – B4	224	2	4
11	Outrigger boom	4	3	2
	Total	740		

The above items, which the TBPOC used to refer to as the 2010 rods, were supposed to be "far better" than the 2008 rods (i.e., S1 and S2 Shear Key base plate anchor rods) that failed in early March. The TBPOC report does not provide the reasons why they need to replace the entire rods of these items. This is like a "group punishment" because of "a few bad apples."

There is no technical justification to replace them all. Perhaps, some rods with exceptionally high hardness, therefore, high susceptibility to HE, may need to be replaced, but certainly not the entire lot.

[84] Reference 9, p. ES-16, 79.

This decision to replace the entire lots of 740 rods was based on the FHWA evaluation results using what they called the Greg Assessment Tool. It uses average hardness data, average toughness data, accessibility, etc. Failures of anchor rods due to HE are determined by the conditions and properties of individual rods, not influenced by an average data for a lot.

Since the decision to replace the 2010 rods was apparently based on the FHWA recommendation, the reasons why they need to be replaced and lack of justification for replacement of the entire lot of 2010 rods will be discussed later in Section 3.0 of this report.

2.15 Lack of Technical Justification for New Supplementary Requirements for Replacement Rods

In addition to the CVN toughness discussed above, the TBPOC report included the following new supplementary requirements for new replacement anchor rods.[85]

> **Revised Specifications for Replacement Rods**
>
> Additional high-strength steel rods are to be purchased to replace the 2010 rods on Pier E2 that have been selected for testing. The remediation strategy outlined above also will require procurement of additional high-strength steel rods. Caltrans has applied supplementary specifications for the rods identified for replacement, which limit the ultimate tensile strength, minimum toughness, maximum hardness and impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring homogeneous metallurgical structure. Caltrans also will be performing the time-dependent hydrogen embrittlement "pull

The TBPOC report has no specific requirements for new replacement rods. The above section only lists what items are to be covered. Lack of metallurgical expertise slips through even in this short paragraph. For example, "impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring homogeneous metallurgical structure" contain several metallurgical problems, as follows.[86] Other items discussed below were proposed as supplementary requirements for "2013 rods" by an "assembled team of experts" on June 7, 2013.[87]

(a) Tight Tolerance on Hardness Range

The word tolerance is inappropriate. It should read, "impose a tight range on hardness." When a new hardness requirement is 31-35 HRC (for "2013 rods") as opposed to 31-39 HRC for ASTM A354 Grade BD, the TBPOC must specify the hardness test location and what is meant by "measured at small intervals across the diameter."

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[85] Reference 9, p. ES-17 and p.83.

[86] The new requirements including the 31-35 HRC hardness requirement came from "A354BD Bolts Testing and Evaluation Meeting: June 7, 2013 @ DJV Field Office, Meeting Notes and Action Items," http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_C_Other_Meetings/C3_A354BD_Bolts_Testing_and_Evaluation_Meeting.pdf

[87] ibid.

The current hardness test protocol according to ASTM F606 is to take hardness readings at mid-radius or at R/2.[88] If the 31-35 HRC applies to the R/2 location, it would be still possible that the surface hardness may reach 39 HRC (Figure 10). This would be unacceptable in view of the failed S2 anchor rods had surface hardness of 36.2 – 36.8 HRC.

For the 2008 as well as for the 2010 rods, the manufacturers, heat treaters, and Caltrans were all unspecific or confused about the hardness test locations. This was one of the main problems why the "2008 anchor rods" of ASTM A354 Grade BD were produced with high surface hardness. So, the new requirement must specify the rod surface as the hardness test location along with any new hardness range requirements.

(b) Homogeneous Metallurgical Structure

A homogeneous metallurgical structure is unattainable in 3 and 4 inch diameter anchor rods, made of 4140 steel, quenched and tempered at around 1000ºF, whether hardness readings are taken at "small intervals across the diameter" or not. This was discussed already on page 11 in reference to Figure 10.

(c) CVN 50 ft-lbs Minimum at 40ºF

As discussed already, CVN toughness tests will not "buy" benefit. Besides, File E17 contains 43 sets of three CVN tests each for Item #7, 3½ inch PWS anchor rods.[89] Only two sets, less than 5%, barely exceeded 50 ft-lbs at 40ºF as well as at 70ºF. CVN test results for other items rarely exceeded 50 ft-lbs. It appears that the 50 ft-lbs minimum at 40ºF is a poor choice as a specification requirement for replacement rods using 4140 as the rod material.

(d) 90% Martensite Transformation

This is not only unnecessary but also cannot work as a material specification requirement. Again, there is a problem with the test location because the 3 and 4 inch diameter anchor rods will have a range of microstructures from the surface to the center. Even with a sample micrograph showing what a 90% martensite looks like, a visual determination of 90% martensite will be problematic and may not be used as a basis of accept/reject. The reason is that a microstructure evaluation is subject to a wide range of personal biases.

Besides, there is no metallurgical evidence that 90% martensite improves or lowers the HE susceptibility. A 90% martensitic structure may produce higher CVN than a mixed structure. As discussed before, however, high CVN toughness will not improve HE susceptibility. In fact, [tempered] martensite ranks higher in HE susceptibility than bainite and fine pearlite. See below.[90]

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[88] ASTM F606 Standard Test Method for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets.

[89] Reference 64.

[90] N. Nanninga, J. Grochowsi, L. Heldt, K. Rundman: Role of Microstructure, Composition and Hardness in Resisting Hydrogen Embrittlement of Fastener Grade Steels, Corrosion Science 52 (2010) 1237 – 1246.
Nanninga et al investigated four carbon steels and three low alloy steels, including 4140.

> A B S T R A C T
>
> The degree of hydrogen embrittlement for several fastener grade steels has been determined. While microstructural alteration resulted in some improvement in resistance to hydrogen embrittlement, the overriding factor contributing to susceptibility of the steel was strength. The degree of susceptibility of the microstructures to hydrogen embrittlement, ranked in increasing order, is as follows: fine pearlite, bainite, tempered martensite. The effects of alloying were also assessed by comparing results from different fastener grade steels with similar microstructures. In most cases, the alloy chemistry had little effect, presumably due to trap saturation associated with this testing technique.

(e) MT (Magnetic Particle Testing) of Threads

Most MT indications in the threads of anchor rods will be linear in the axial direction. Since the anchor rods are stressed in the axial direction and no cyclic stresses are involved, there is really no need for MT regardless of pretension levels. Conversely, more handling damage to the threads can occur during MT. MT can also leave residual magnetism, which can create problems in achieving and maintaining the best surface cleanliness before hot dip galvanizing.

(f) Thread Forming

Thread forming by cold rolling before the final heat treatment (hardening and tempering) poses no problems and would be acceptable.

For new anchor rods, thread forming by cold rolling after full heat treatment should be banned until after anchor rods with such threads can be shown to have performed as well as cut threads through field performance data, not based just on a few lab tests, including Townsend tests. In a strict sense, anchor rods with rolled threads do not comply with the intent of the heat treatment requirements for ASTM A354 Grade BD because the cold work effects of the thread rolling alter the properties of the heat treated condition.

The effects of cold rolled threads of fully heat treated rods on HE susceptibility are unknown, particularly for those that were subsequently hot dip galvanized. In fact, ASTM A143 states as follows regarding the effects of cold work on hydrogen embrittlement.[91]

> 4.2 Hydrogen embrittlement may also occur due to the possibility of atomic hydrogen being absorbed by the steel. The susceptibility to hydrogen embrittlement is influenced by the type of steel, its previous heat treatment, and degree of previous cold work.

Figure 21 shows what a 3 – 4UNC anchor rod with rolled threads looks like. It starts out with a rod that has a diameter equal to the pitch diameter (2.837 inch for 3 inch rods) and the threads are cold formed by die rolling. So, the entire volume of the threads with a 0.149 inch depth will have a cold worked structure. The problem will be at the thread roots, which are also cold worked, resulting in high localized hardness along the root surface layer of threads.

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[91] ASTM A143 Standard Practice of Safeguarding Against Embrittlement of Hot Dip Galvanized Structural Steel Products and Procedures for Detecting Embrittlement.

Items No. 4, 7, 8, and 16 in Figure 2 have rolled threads, for a total of 492 rods, from 2 to 4 inches in nominal sizes.

Item No. 7, 3½-inch PWS (Parallel Wire Strands) Anchor Rods, ASTM A354 Grade BD, HDG, is particularly of concern. There are 219 of this item with rolled threads for the main cable. In this case, heat treated steel rounds, 3.52-inch in diameter, from Gerdau and 3.75-inch in diameter from Steel Dynamics, were turned down to a required pitch diameter (i.e., 3.33-inch for 3½-inch - 4UNC threads). Dyson roll formed the threads on these fully heat treated bars, followed by grit blasting and hot dip galvanizing. Gerdau reported 37.1 to 38.8-HRC at the surface of the 3.52-inch rounds and Steel Dynamics 35 – 36-HRC at mid-radius for their 3.75-inch rounds, both after heat treatment. It is possible that the hardness at the roots of cold rolled threads could have increased to well above 40 HRC.

The fracture face of a PWS anchor rod sample in Figure 15a shows no indications of the effect of cold working around the thread root. The hardness traverse data in Figures 15b and 15c also have no indications of the effects of the increased hardness at thread roots.[92] This is probably because the sample rods for a full size tensile test, hardness test, metallographic and SEM evaluation, CVN test, and chemical analyses of the steel and the zinc coating were selected at random without specific purpose of determining the cold work effects of the rolled threads.

Figures 22 and 23 present part of a massive amount of data generated for Item #7, 3½ inch PWS anchor rods in File E17. None was useful in determining the effects of cold rolled threads, including the data presented in Figure 23a. It was apparently intended to show no differences were found between the rods with cut threads and those with rolled threads. However, what is missing is the recognition that neither the lab Rockwell hardness tests nor the field portable hardness tests are useful in determining the effects of the cold thread rolling on hardness unless the test method was specifically directed toward that purpose. This could be best accomplished by microhardness tests, either in the HK or the HV scale.

"All tests, except for Tests IV [Townsend Test] and V [Raymond Test] were completed by June 21, 2013" without determining the hardness at the root surface of rolled threads. None of Caltrans' field hardness test data in File E17 was directed toward finding out the hardness at the thread root, which would be an important area from the point of HE failures. Even the Knoop hardness data in Figure 15c were useless regarding the effects of cold rolling of the threads. The above suggests that Caltrans engineers do not know what is important and what to look for in conducting a large number of tests on the ASTM A354 Grade BD rods on the SAS Bridge.

Caltrans is aware of the fact that the PWS anchor rods have rolled threads. They are not fully cognizant, however, of the significance of the effects of cold rolling on the microstructure, hardness, and susceptibility to HE. The test data in File E17 have nothing useful for anchor rods with rolled threads. Therefore, none of the hardness data for Item #7 is useful in evaluating the susceptibility to HE or as a tool for screening specimens for the Townsend Test.

[92] File E17 contains many HK hardness traverse data like that in Figure 15c. None of the HK data had the applied test force used, as recommended for HK data presentation by ASTM E384, para. 5.8.1.

In summary, out of six or seven items of new supplementary requirements, only the new hardness range, 31 – 35 HRC, makes sense. This may be perhaps expanded to 31 – 36 HRC when the hardness test location is specified as shown below. It is vitally important to specify the rod surface as the hardness test location because it is commonly misunderstood and because the hardness at the surface is what counts in connection with HE susceptibility.

All ASTM A354 Grade BD replacement anchor rods for the SAS Bridge should meet the following hardness requirements.

(1) Each rod shall be hardness tested at the rod surface in the location next to the ends of the threads at both ends. Portable hardness tester may be used.

(2) The surface hardness shall be in the range of 31-36 HRC.

The 31 – 35 HRC range at the rod surface could be too narrow to be practical for 3 and 4 inch diameter anchor rods. To meet the 140 ksi minimum tensile strength, the rods must have around 31 HRC or higher at R/2 (mid-radius). This would require the surface hardness of 35 HRC or higher.

Also, TBPOC/Caltrans must consider why the S1 and S2 anchor rods failed on Pier E2 in the first place. They failed because they were subjected to wetness for a prolong time in the bottom threads. That was a unique occurrence that will not be repeated on the SAS Bridge any more. The SAS Bridge now has no chance of having such mishaps. The worst condition that needs to be worried about is a full exposure to the marine atmospheric environment of the San Francisco-Oakland Bay, which is very different from a continuous wetness in stagnant pools of water. The TBPOC/Caltrans needs to evaluate if EHE of Grade BD rods in the atmospheric service is different in severity from EHE in pools of stagnant water.

2.16 Inconsistent Technical Data in the TBPOC Report

Table 13 of the TBPOC report is partially reproduced in Figure 24.[93] First of all, this table, which runs four pages, is labeled "Table 13 Summary Results of Testing for Susceptibility to SCC." This is mislabeled; the contents of the table have nothing to do with the SCC test (or the Townsend Test). This table presents a summary of Test I (in-situ field hardness test), II (lab tests such as HRC, CVN, tensile tests and metallographic evaluation), and III (full size tensile test). This table would have been useful; but it is not because it is full of erroneous or questionable interpretation of test data.

(a) Surface Hardness of Tested Rods (HRC)

In Figure 24, Item #1 lists 37.6 HRC average with a range of 36.9 – 38.2 under "Surface Hardness," in the fourth column from the left. These hardness data are not exactly the same as what Anamet Labs reported: 36.8 – 38.2 HRC for S2-A6 #12 and 36.1 – 36.4 for S2-A6 #2.[94] Then, Item #7 (PWS – main cable anchor rods), lists 35.9 HRC average with a range of 25.1 – 38.9 HRC. It seems improbable for 3.5 inch 4140 steel anchor rods to have surface hardness as low as 25.1 HRC because the rod would have never met the minimum tensile strength requirements when the surface hardness was 25.1 HRC.

[93] Reference 9, pp. 70 – 73.
[94] Anamet Report No. 5004.8612 and 5004.8677.

Conversely, many hardness traverse data in File E17 would be flat across the diameter, if plotted, because of little differences between the hardness near the circumferential surface and the core. Examples are shown in Figure 25. These flat hardness data would represent the “end quench effect.” It would be possible that the cross sections with flat hardness data were the ends of the rods when they were hardened and tempered. This is the very reason why ASTM F606 (3.1.3) requires an arbitration hardness test on a cross section approximately one diameter from the thread end to void the end quench effect.

It appears that no differentiations were made between the hardness traverse data that would be bowl shaped across the diameter and those that would be flat when plotted. These flat hardness traverse data would have contributed to a high average hardness for the lot. An average hardness should have been taken from hardness data that represented the same cross sections, that is at least one diameter distance from the ends that were hardened.

It is possible that Caltrans engineers have called all field hardness tests as a surface hardness test because the hardness test is done on a flat surface of a cross section. In the case of rounds such as anchor rods, the surface would mean the circumferential surface, not the flat surface of a cross section. The same question applies to Items #2 and #3 as well. The TBPOC needs to define what is meant by the “Surface Hardness” in Table 13 (and Figure 34).

Item #7 is particularly worrisome. This is because 80% of 274 or 219 anchor rods for the main cable (PWS) have threads that were formed by cold rolling round rods that had been fully heat treated to 38.8-HRC at the circumferential surface. Therefore, the hardness at the root of the rolled threads should have a hardness much higher than 38.9 HRC in Figure 24, probably well above 40 HRC, as discussed before. Caltrans needs to determine the hardness at the thread roots for Item #7 and investigate the effects of cold rolled threads on EHE (or *long-term stress corrosion cracking*).

Caltrans may not use the dehumidification of the splay chambers as the sole justification for doing nothing more. Caltrans needs to specify the maximum relative humidity for the chambers and ascertain that the susceptibility of the PWS anchor rods with rolled threads is not higher than that of rods with cut threads of equal hardness.

(b) Microstructure (Third Column)

Only Item #1, Shear Key S1 and S2 base plate anchor rods, classified as the 2008 rods, is listed as having “incomplete martensite transformation.” Its surface hardness is listed as 37.6 HRC average with a range of 36.9 – 38.2 HRC. The rest (except for the 8 items not tested out of the 17 items in the entire Table 13) were all listed as “essentially martensitic,” including Item #7 that lists hardness as low as 25.1 HRC as surface hardness. This low hardness value is not consistent with an “essentially martensitic structure.”

It is probable the metallurgist who made this determination of an “essentially martensitic structure” for all the items tested must have a different concept of a martensitic structure from the authors of the ABC report who examined the failed anchor rods. This is the very reason why a “90% martensite” will not work as a supplementary requirement for replacement anchor rods. The entire column of “Microstructure” does not make sense because none of 3 and 4 inch diameter Grade BD rods, made of 4140, would have an “essentially martensitic structure” across an entire cross section.

(c) Mode of Fracture

It is difficult to understand why this column was even necessary. None of ASTM specifications has a requirement for a fracture mode. It is also curious what the bases of deciding the mode of fracture as to ductile or brittle were. As discussed already (on page 27 in reference to Figures 13 and 14), steel fracture faces consist usually of mixed modes, brittle zones and ductile zones.

Again, in Figure 24, only Item #1 (the 2008 rods for Shear Keys S1 and S2) lists "brittle" and all the rest "ductile." Not only can all the rest of the 16 items not have a ductile mode of fracture but also the "brittle" applies only to the field failure samples because they failed due to HE. None of Item #1 was tensile tested in a full size under the same monotonically rising conditions as for Items #2 - #16.

The mode of fracture listed in Figure 24 does not even correlate to the CVN data in the next column. For example, Item #15 lists 17 – 18.7 ft-lbs CVN. The CVN specimens with these values cannot have fracture faces that may be classified as "ductile." Also, Caltrans provides no explanations as to what is meant by QC/QA data.

Therefore, the entire entry under the "mode of fracture" column in Table 13 (partially reproduced in Figure 24) is useless and should not be included in the test data summary.

2.17 Hardness Data Requiring Metallurgical Evaluation

As mentioned before, File E17 contains a massive amount of hardness test data, laboratory and field, using MIC 10 microhardness tester and the procedure shown below.

GENERAL PROCEDURE:

1) Galvanizing was ground off the top surface of the rods using a grinder.
2) Suitable sand paper was lightly applied after grinding to achieve a surface profile of 15 μm or less per ASTM A1038.
3) A profile meter was utilized to ensure surface roughness is acceptable.
4) The surface was free from oil, grease, dust, rust, and surface coatings.
5) Measurements were taken as shown on Section A above.
6) After measuring the hardness on each rod, the equipment readings were verified against a certified hardness reference block by taking 2 additional measurements.

Figure 22 presents an example of these hardness test data and corresponding hardness traverse graphs for two cases of Item 7, 3½ inch PWS anchor rods. The shortcomings of these data, specific to the anchor rods with rolled threads, were already discussed.

A typical hardness traverse curve for 3 or 4 inch 4140 steel anchor rods, quenched and tempered to meet the requirements of ASTM A354 Grade BD, will typically be bowl shaped like that in Figure 10 or open-V shaped like those in Figure 23.

Many hardness data would look flat rather than bowl shaped if plotted as mentioned already. Some examples of flat hardness traverse data are shown in Figure 25.

Also, many of the hardness traverse curves in File E17 were M-shaped. Several examples are presented in Figure 26. These hardness data are atypical of 4140 steel rounds, quenched and tempered. Caltrans should have provided some explanation as to the M-shaped hardness traverse data and their effects on the susceptibility to HE. If no acceptable metallurgical explanations are readily available, Caltrans should have done a metallurgical evaluation to determine why the hardness traverse data are M-shaped and what their effects may be with regards to their integrity against EHE failures.

Caltrans need to conduct metallurgical investigations to determine the reasons why the hardness traverse data are either flat or M shaped and to evaluate their effects of HE susceptibility.

3.0 ERRORS IN THE FHWA REPORT

3.1 FHWA Review of the TBPOC Report

In response to the TBPOC's request, the FHWA produced a ten page report by a seven member team, as follows.[95]

San Francisco-Oakland Bay Bridge Seismic Safety Project

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

The FHWA review of the TBPOC report found it to be completely acceptable when in fact the TBPOC's conclusions on the S1 and S2 anchor rod failures were highly questionable and inconsistent with the failure pattern. The FHWA's review of the TBPOC report and test data lacked criticality and technical expertise in the failure mechanisms of high strength steel bolts/rods. It also emphasized to require supplementary requirements, including minimum toughness, for replacement anchor rods, which are not warranted as discussed above.

One of the recommendations in the above report is as follows.

2. Use the Greg Assessment Tool *[See Appendix B]* developed by FHWA for determining the vulnerability of the bolts to hydrogen embrittlement or stress corrosion cracking.

The Greg Assessment Tool uses several metallurgical factors with "Weighting Factors" to derive ranking of susceptibility of high strength steel rods to EHE (or stress corrosion cracking). As discussed below, the factors are arbitrarily chosen and the "Weighting Factors" arbitrarily assigned.

This methodology has a serious problem as to its applicability to high strength steel anchor rods.

[95] FHWA Review of A354 Grade BD Bolts Used in the Self-Anchored Suspension Bridge, by the FHWA Review Team, August 2013, http://www.mtc.ca.gov/pdf/FHWA_SAS_Bolts_Report_August_2013_-1.pdf

3.2 Questionable Premises and Assumptions for Greg Assessment Tool

The Greg Assessment Tool was developed by FHWA engineers.

It evaluates risk categories for high strength steel anchor rods as shown below.

Table 2: Risk Category Weighting Factors

Environment and Access	Applied Tension	Ave. Rockwell Hardness	Redundancy	Ave. Tensile Strength	Ave. Charpy Toughness
2.5	N/A	N/A	N/A	N/A	N/A
2.0	2.0	2.0	1.5	1.5	1.5
1.5	1.5	1.5	1.0	1.25	1.25
1.0	1.0	1.0	0.5	0.75	0.75

The "Environment and Access" has four classifications, as follows, with the "Weighting Factors" shown above.

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

Each of the next five categories has three classifications according to the actual tension level and actual test data, as follows.

Table 2: Risk Category Weighting Factors

Environment and Access	Applied Tension	Ave. Rockwell Hardness	Redundancy	Ave. Tensile Strength	Ave. Charpy Toughness
2.5	N/A	N/A	N/A	N/A	N/A
2.0	2.0	2.0	1.5	1.5	1.5
1.5	1.5	1.5	1.0	1.25	1.25
1.0	1.0	1.0	0.5	0.75	0.75

Then, the sum of weighted scores is classified as follows.

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

The FHWA evaluated the 17 items in Figure 2. Below is a partial display of the results.

Location	Grp	Description	Type	Thread	Risk Environment	Hardness	Risk Hardness	Overall Category
Pier E2 Cap	1	Shear Key (S1, S2)	Rod	Cut	[illegible]	37	High	Severe
Pier E2 Cap	1	Shear Key (S1, S2)	Rod	Cut	Severe	37	High	Severe
Pier E2 Cap	2	Shear Key (S3, S4)	Rod	Cut	High	34	Low	Moderate
Pier E2 Cap	2	Bearing (B1-B4)	Rod	Cut	High	34	Low	Moderate
Pier E2 Cap	2	Bearing (B1-B4)	Rod	Cut	High	34	Low	Moderate
Pier E2 Top	3	Shear Key (S1, S2)	Rod	Cut	High	35	Moderate	High
Pier E2 Top	3	Shear Key (S1, S2)	Rod	Cut	High	35	Moderate	High
Pier E2 Top	3	Shear Key (S3, S4)	Rod	Cut	High	35	Moderate	High
Pier E2 Top	3	Shear Key (S3, S4)	Rod	Cut	High	35	Moderate	High
Pier E2 Top	4	Bearing (B1-B4)	Rod	Cut	High	35	Moderate	High
Pier E2 Bearing	5	Bearing Bushings (B1-B4)	Rod	Cut	Severe	34	Low	High
Pier E2 Bearing	6	Bearing Retaining Rings (B1-B4)	Cap Screw	Cut	Severe	35	Moderate	High
Cable Anchorage	7	PWS Anchor Rods and Sockets	Rod	55 Cut & 219 Rolled	Low	36	Moderate	Low

This methodology has the following problems that would make the results highly quesitonable as to their validity.

(a) The "risk category weighting factors" are based on average test data such as "Ave. Rockwell Hardness" and "Ave. Charpy Toughness," as indicated in Table 2 of the Greg Assessment Tool.

The susceptibility of any particular high strength steel rod to HE is determined by its own properties, for example, the surface hardness specific to that particular rod, not by an average hardness data for a group of several hundred rods. Thus, this methodology is based on a faulty premise.

For Item #7, PWS (Parallel Wire Strands, main anchor cable), the last row in the above table, 36 HRC was used for hardness. This was apparently based on the "Average of All Test Data" shown in Figure 23b. It shows that the surface hardness at 0.25 inch from the surface ranged between 27 – 39 HRC. Even these hardness data are useless for the anchor rods with rolled threads. As discussed before, the hardness of the surface layer of the root of cold rolled threads would be much higher than that indicated by Figure 23b. The Greg Assessment Tool does not take the effect of cold work in the surface layer into consideration. Thus, it is not applicable to the anchor rods with rolled threads or any other rods that do not fit the data used.

(b) Likewise, the "Ave. Tensile Strength" and "Ave. Charpy Toughness" in Table 2 of this methodology are inappropriate for assessing the HE susceptibility of individual rods.

(c) The "Weighting Factors" for "Ave. Rockwell Hardness" are 1.33 times those for the "Ave. Tensile Strength" or "Ave. Charpy Toughness for **high** and **low**.[96] This ratio is, however, 1.2 for **moderate**.[97] Thus, the scaling ratios, for whatever the original technical reasons, are inconsistent.

[96] 2.0/1.5 = 1.33.
[97] 1.5/1.25 = 1.2.

(d) There is no technical justification why the “Ave. Charpy Toughness” should have the same “Weighting Factors” as those for the “Ave. Tensile Strength.”

To be acceptable, the Greg Assessment Tool needs to address the questions in Table 4, items 14 – 18.

4.0 FAILURE OF CALTRANS DIRECTOR AS ENGINEERING-CONSTRUCTION PROJECT MANAGER

The TBPOC and Caltrans have repeatedly erred from simple tensile test fracture interpretation, to the meaning of the Townsend Test, and to the summary table of all test results in the TBPOC report with numerous errors. They have had several bloopers during BATA briefings. They have produced a document purporting to explain and address the failure of key anchor rods on the SAS Bridge that is littered with 177 errors and questionable statements for a public works project costing $6.4 billion.

Prof. Thomas Devine served as Chairman of the Materials Science and Engineering Department from 1996 to 2002 at the University of California, Berkeley. In an interview with the PBS, he said the “bolt failures [on Pier E2] should have been foreseen.” He said that one of the reasons that these failures happened was that TBPOC/Caltrans did not have proper engineers or “metallurgists in place.”[98]

Between March 27 and July 10, 2013, TBPOC/Caltrans gave six briefings about the failed anchor rods on Pier E2 to BATA Commissioners and to the public. These briefings were all presided and presented by the TBPOC members and Caltrans engineers. No materials engineer with expertise in the metal failure mechanisms, especially in stress corrosion cracking, hydrogen embrittlement, or both, came to the Briefings and gave a presentation. One of the presenters would use stress and strength interchangeably, which is an egregious error in engineering. This same error can be found also in the TBPOC report, in five places. (See Table 1, items 5 and 13, and Table 3, items 20, 48, and 129.)

Four months after the S1 and S2 anchor rod failures on Pier E2, the TBPOC and Caltrans still did not have proper engineers who could advise the Caltrans Director that what he had presented at the BATA Briefing was wrong and why. Instead, an observation by the TBPOC Chairman in May that tensile test fractures in a lab looked more ductile than field fractures due to HE solidified in July as a significant finding. The Caltrans Director has had no one within his organization who could advise him that the ABC report lacked thoroughness in metallurgical evaluations and their conclusions were inconsistent with the failure pattern of the 32 anchor rods.

The July 8, 2013 TBPOC report with the numerous errors has demonstrated that Caltrans has no materials engineers who could have produced or reviewed a technical report that is reasonably acceptable with contemporary scientific understanding of metal fracture mechanisms, including hydrogen embrittlement. Even now (as of October 2013), they do not seem to have expertise in materials engineering, with the particular expertise necessary in dealing with the hydrogen embrittlement cracking problems of high strength steel anchor rods.

[98] http://www.pbs.org/newshour/bb/nation/july-dec13/bridge_08-12.html

The "buck" stops with the Caltrans' Director; he has the responsibility to assure they have engineers with the requisite knowledge and skills to resolve the issues including materials engineering related problems. The S1 and S2 anchor rods failed on Pier E2 in March 2013 and four months later, TBPOC-Caltrans released a report with numerous errors, all because Caltrans lacks engineers who have expertise in the metallurgy of large anchor rods (up to 1,100 pound each). The Caltrans Director has failed as an engineering-construction project manager.

5.0 NEED FOR REFORM AT CALTRANS

It is disappointing that the FHWA was unable to find any errors with the TBPOC report when in fact it has many errors, minor and major, including an incorrect conclusion regarding the S1 and S2 anchor rod failure mechanism. Even more disappointing is that the FHWA contributed to the problem when it recommended the TBPOC use the FHWA's Greg Assessment Tool in dispositioning the entire high strength steel rods on the SAS Bridge and TBPOC/Caltrans complied with the FHWA recommendation without due deliberation.

The FHWA's Greg Assessment Tool is based on highly questionable premises and assumptions. The validity of its risk assessment results is open to question. TBPOC/Caltrans has apparently used this recommendation from the FHWA as an endorsement for the replacement of the 740 high strength steel anchor rods that had already been installed.

There are not any techncal reasons why all of them should be replaced based on average test data when the HE failure of an individual rod is governed by its own properties. Whether a particular rod might fail due to IHE or EHE or not would be unaffected by any average test data such as average hardness for the lot to which that rod belongs. It does not make sense to "punish" an entire lot because of a few "bad apples." The Greg Assessment Tool by the FHWA is "philosophically flawed." Yet, TBPOC/Caltrans adopted the Greg Assessment Tool without due deliberation. Conversely, the FHWA agreed completely with TBPOC/Caltrans regarding the "Findings and Decisions" when they were found to be wrong, including the conclusions as to the metallurgical cause of the S1 and S2 anchor rod failures.

This type of blind mutual trust has come about because of the insular culture at government agencies as decried in the Bay Area media.[99,100] This unacceptable trend has resulted because Caltrans has no accountability. Caltrans has been allowed "to investigate its own problems and report the results back to itself." When the TBPOC invited the FHWA to provide a "peer review," the FHWA could not do a fair or critical job of reviewing TBPOC/Caltrans because they are all in the "same boat." In this regard, the panel of world renowned consultants to TBPOC/Caltrans has not made any critism of their handling of the anchor rod failure problems or their "Findidings and Decisions." Again, this is because the panel of esteemed consultants has a conflict of interest in criticizing the "employer."

[99] Daniel Borenstein: Despite Construction Chaos and Incompetence, Bay Bridge Official's Insular Culture Persists, San Jose Mercury News, July 11, 2013, http://www.mercurynews.com/ci_23643498/daniel-borenstein-despite-construction-chaos-and-incompetence-bay

[100] Sen. Mark DeSaulnier: The Culture at Caltrans Must Change, Contra Costa Time, May 11, 2013, http://www.contracostatimes.com/ci_23210094/sen-mark-desaulnier-culture-at-caltrans-must-change

The July 10, 2013 BATA Briefing was particularly noteworthy because it was attended by the three members of the TBPOC, Caltrans' East Span Project Management Team members, Caltrans' Chief Bridge Designer, the California Division Administrator of the FHWA, and the three members of the Seismic Safety Peer Review Panel (SSPRP) for TBPOC/Caltrans.[101] SSPRP's Vice Chairman, Professor Emeritus Frieder Seible, made an impromptu presentation about the idea of "shimming the bearings" to make them act like shear keys to allow the New East Span to open to traffic as scheduled in September. During this presentation, he stated, "All the other recommendations in this report are perfectly fine and we fully agree with it, OK?" Professor Emeritus John Fisher was also there, watching the presentation by the Caltrans Director about Figure 12, sitting next to the third member of the SSPRP. All three are members of the National Academy of Engineering.

Any engineer with basic materials engineering skills at the Briefing should have known that the Caltrans Director was not making sense when he compared the brittle fracture due to EHE with "a ductile fracture" in lab tensile tests in Figure 12. Almost nobody has criticized the errors in the ABC report, the TBPOC report, or Caltrans' mismanagement of the S1 and S2 anchor rod failures and their aftermath. TBPOC/Caltrans with its panel of consultants cannot find their own errors, let alone fix them. This is the result of a lack of expertise in materials engineering and failure analysis or more likely to be due to conflicts of interest whereby knowledgeable individuals felt restrained from offering full and frank advice.

This has led to

(a) the selection of hot dip galvanized ASTM A354 Grade BD for fracture critical anchor rods without proper assessment of both IHE and EHE risks,

(b) mechanical galvanizing being specified for anchor rods that were too large and heavy to be accommodated by the process until a supplier pointed out the obviously faulty requirement,

(c) TBPOC/Caltrans to use this faulty requirement (mechanical galvanizing) as an excuse that Caltrans engineers were at least cognizant of HE problems with hot dip galvanizing when they were concerned only about IHE but not about EHE (or *long term SCC*),

(d) TBPOC/Caltrans assuming that requiring abrasive dry blasting instead of acid pickling prior to hot dip galvanizing would avoid all HE (both IHE and EHE) risks,

(e) Caltrans fumbling around to determine the HE as the anchor rod failure mechanism when it was the only possible mechanism to account for the 32 high strength steel anchor rod failures under static load at room temperature,

(f) a TBPOC report with 177 errors and questionable statements, with the wrong conclusion as to the metallurgical cause of the anchor rod failures, and with important questions unanswered regarding the long term performance of critical anchor rods (the PWS and the tower base), and

(g) the acceptance of a "peer review" report by the FHWA and its Greg Assessment Tool that is worth little.

The above series of incompetent decisions and actions involving the high strength steel anchor rods over ten years is possible only because Caltrans' culture has allowed them to happen.

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[101] See Reference 9, p. 95.

SB (Senate Bill) 486, creates the Office of Legal Compliance and Ethics. It “aims to begin fixing the ‘peer review’ process of our state's public works projects. Public works projects touted as ‘peer reviewed’ should live up to the public's expectation of what the term really means. SB 425 sets the standard that a peer review is transparent and has been conducted by panelists free of conflicts of interest.”[102]

There is a need for a meaningful reform at Caltrans. It must be made accountable to the public.

6.0 CONCLUSIONS

(1) The July 8, 2013 TBPOC report on the ASTM A354 Grade BD high strength steel anchor rods on the SAS Bridge concluded that the shear key anchor rods on Pier E2 failed in early March 2013 due to “*short term hydrogen embrittlement*.” This is the same as *internal hydrogen embrittlement* (IHE) in the context of the TBPOC report. This is wrong because IHE is inconsistent with all 32 failures occurring in the bottom threads.

(2) The 32 anchor rods failed all in the bottom threads due to environmental hydrogen embrittlement (EHE). In the TBPOC report, EHE is referred to as “*long term stress corrosion cracking (SCC).*” The hydrogen responsible for these failures came from the corrosion of the bottom threads while they were exposed to pools of stagnant water for a long time.

(3) Therefore, Caltrans and its contractors who failed to protect the high strength steel anchor rods properly from corrosion during the construction delay period are responsible for the anchor rod failures on Pier E2.

(4) The shear keys could have used ASTM A354 Grade BC anchor rods instead of Grade BD anchor rods without incurring basic design changes. The former could have been hot dip galvanized without the danger of failures due to internal hydrogen embrittlement (IHE), EHE (or long term SCC as used by the TBPOC), or both. Since Grade BC is not susceptible to HE, the anchor rod failures on Pier E2 in March 2013 could have been avoided.

(5) Caltrans and its contractors selected ASTM A354 Grade BD, hot dip galvanized, without diligent evaluations of both IHE and EHE problems. They were concerned only about IHE and not about EHE. Thus, the root cause of the anchor rod failures on Pier E2 was lack of expertise in materials engineering by Caltrans and its contractors.

(6) The TBPOC report lists nine findings. Of these, Findings 1 (rod material having higher than normal susceptibility to HE as the root cause), 3 (need for proprietary high strength steel), and 8 (ASTM A143 embrittlement test could have detected the HE problems) are invalid.

(7) The TBPOC report states that the failed anchor rods could have been improperly heat treated. The ABC metallurgical failure analysis team conducted no heat treatment experiment to verify if the improper heat treatment contributed to the failures. An additional heat treatment is not one of factors that could have contributed to the anchor rod failures.

[102] http://www.legtrack.com/bill.html?bill=201320140SB425

(8) Except for a new hardness range (31 – 35 HRC) for replacement Grade BD anchor rods, other items in supplementary requirements (such as 50 ft-lbs CVN at 40ºF) may be either unnecessary or need technical evaluation as to their efficacy in lowering the susceptibility of Grade BD rods to hydrogen embrittlement.

(9) The Caltrans test data for Item #7, PWS, lack hardness data for the surface of the root of cold rolled threads. Also, Caltrans has not done sufficient evaluation of the effects of cold rolled threads on EHE. None of the massive amount of hardness data is useful for the Grade BD rods that were fully heat treated and cold rolled to form the threads.

(10) The hardness data for the tower base anchor rods need further metallurgical evaluation to understand their significance on their long term integrity, including their bottom ends.

(11) The FHWA review report of the TBPOC report is unacceptable because it failed to find numerous errors, proposed unnecessary requirements for replacement rods, and proposed an inconsistent and unjustifiable risk assessment evaluation protocol.

(13) The FHWA's Greg Assessment Tool lacks technical justifications as to the premises and methodology used.

(14) The TBPOC report contains numerous errors, from simple typographical errors to major technical errors. The July 8, 2013 TBPOC report is unacceptable as a public document.

7.0 RECOMMENDATIONS

(1) The TBPOC should issue a new report on the ASTM A354 Grade BD rod failures on the SAS Bridge. The new report should address the questions listed in Table 4 (page 71).

(2) The new supplementary requirements for replacement rods should include the rod's circumferential surface as the hardness test location for the new hardness requirements (31 – 35 or 31 - 36 HRC).

(3) The metallurgical tests including hardness tests, particularly for those for the main cable and the tower base, must be redone.

(4) High strength steel rods with threads formed by cold rolling after heat treatment should not be allowed until after the effects of cold working on hydrogen embrittlement susceptibility have been fully evaluated, including field performance data.

(5) The 3 and 4 inch anchor rods for the tower base have M-shaped hardness profiles across the cross sections. The reasons for this peculiar hardness profile and its effects on the susceptibility to hydrogen embrittlement should be evaluated.

(6) Hydrogen embrittlement cracking can be promoted by cathodic protection. Ascertain that the bottom ends of the tower anchor rods will not be adversely affected by a cathodic protection system, if any.

(7) No decisions should be made as to the disposition of ASTM A354 Grade BD rods based on the results of an evaluation using the FHWA's Greg Assessment Tool.

(8) Make Caltrans accountable to the public.

Table 1

List of Typographical and Other Simple Editorial errors in the TBPOC Report

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Errors	Comments
1	ES-1	the SAS Bridge?;	Remove the semi-colon after a question mark.
2	ES-2	of the rods?;	Remove the semi-colon after a question mark.
3	ES-4	Overhead View	Change to "Plan View"
4		Cross-Section View	Change to "Elevation View"
*5	ES-10	The three conditions of susceptible material, high tensile strength and the presence of hydrogen all were present, leading to	"high tensile strength" should be "high tensile stress."
6	ES-17	impose a tight tolerance on hardness	The word "tolerance" is incorrect. Change to "a tight range."
7	ES-18	ample evidence exists than none are	"than" is a typographical error for "that."
8	1	in 2008, on Pier E2 of the SAS Bridge?;	Remove the semi-colon after a question mark.
9	1	the lost clamping force of the rods?;	Remove the semi-colon after a question mark.
10	12	[1]Brahimi, Salim, Rosme Aguilar, and Conrad G1 & S2-A6", May 7, 2013.	This reference is dangling without being keyed in the text. "Brahimi, Salim" should be changed to "Salim Brahimi" to be consistent with other authors' names.
11	18	with the outer diameter approaching 39 HRC	The "outer diameter" is inappropriate because the rods have no inner diameter.
*12	19	A rectangular specimen with a 'V' shaped notch	The CVN specimen is not known as a rectangular specimen among materials engineers. It is known as a square specimen (10mm x 10mm) in the same way as the tensile specimens with a round cross section is referred to as round specimens, rather than slender specimens.
*13		causing cracking and brittle failures at stresses below the yield stress of of susceptible materials.	"the yield stress" is the yield strength.

Table 1 (Continued -2)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Errors	Comments
14	21	While the specified hardness range for ASTM 354 grade BD bolts and rods	Should be ASTM A354, not ASTM 354.
15	26	A354 Grade BC 125 3.5 strength between 115 and 125 ksi	The "125" should be "115 for 3.5 inch diameter, not between 115 and 125 ksi.
16	39	and tensile strength, for various diameter rod sizes.	Not various. Only for two size groups, 1/4 - <2½ and 2½ - 4.
17	51	Item #5 in Japan	This should be "in Korea."
*18	52	Vacuum degassing removes hydrogen or carbon.	The word carbon is incorrect. It should be either carbonaceous gases or carbon dioxide and mono-oxide gases.
19	57	as a guide the published research of John.W. Fisher[12] and H.E. Townsend[13]	Remove "John W. Fisher and." He published no original research paper on hydrogen embrittlement or stress corrosion cracking.
20		John.W. Fisher[12] and H.E. Townsend[1]	Remove the period after "John" or change to J. W. Fisher.
21		J.W., Struik,	Remove the extraneous comma after W.
22		*2nd Edition,* Kulak, G.L. Struik, J.H.A. in 1987.	Change 1987 to 2001.
23		[13] H.E. Townsend is a Research Supervisor of the Corrosion Prevention Group within Homer Research Laboratories	This should be "H. E. Townsend was a Research …."
24	58	His re- search found that electroplated	"His research" should be "Townsend's research …"
25		Figure 24 ***In-situ* Hardness Test on Bearing Rod**	Caption mislabeled. Should be "in-situ Hardness Test on Shear Key Anchor Rod."
*26	59	hardness, toughness, mechanical properties, and chemical composition.	Need to reword. "mechanical properties" comprise hardness, toughness, tensile strength, etc.
27	59	**Test IV** Test IV (Townsend Test) replicates the earlier Townsend research	The "earlier Townsend research" used small precracked cantilever beam specimens, not full size anchor rods with threaded ends. Therefore, Test IV does not "replicate" his earlier research.
28	61	Number of Heats	This table, SAS A354BD Bolt Tests, lists 7 under Number of Heats for Item 1, "Shear Key Anchor Bolt Bottom. This is incorrect. Item 1 has one or two heats with identical chemical compositions.
29		*, **	These marks have no explanatory notes.

Table 1 (Continued -3)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Errors	Comments
30	68	corrosion cracking, per guidance from Dr. Fisher.	This should be "per guidance from Dr. Townsend" and the Test IV protocols were developed by Townsend, Frank, and Williams, not by Fisher. Dr. Fisher published no original research papers on corrosion, stress corrosion cracking, or hydrogen embrittlement.
*31	69	The ordinate is mislabeled. The abscissa may also be mislabeled. For example, Item #7 may not have 25 HRC as surface hardness.	It is supposed to be K_{ISCC}, not K_{IC}. Either way, it would be meaningless to plot it against a range of hardness. Figure 34 is unintelligible.
32	70	Table 13 Summary Results of Testing for Susceptibility to SCC	This is mislabeled. Table 13 has no data on SCC.
33	72	Table 13 Summary Results of Testing for Susceptibility to SCC	
34	87	Malcolm Doughterty	Dougherty misspelled. Write Dougherty.
*35	88	An impact test in which a rectangular specimen	Should read, "a square specimen."
36		Grade BD rods are 140 ksi for 25/8	Should write "2 5/8-inch" or "2⅝-inch."
*37	90	As specified in ASTM D785, the indenters	ASTM D785 is for plastics. The correct one for metals is ASTM E18.
38	91	cooled slowly from a high temperatures.	Should be "a high temperature."
39	93	Tension Member Any member of a truss	Tension Member does not appear anywhere in the report.
*40		Vacuum Degassing A process where molten ... order to remove excess hydrogen or carbon.	Vacuum degassing does not remove carbon. Vacuum oxygen degassing does.
*41		By removing the carbon, the metals become more ductile, or easily shaped and	Erroneous and misleading.
42		Metallurgical Investigative Team In May 2013, a metallurgical investigative team was tasked with examining the cause of	"May 2013" is incorrect. It had to be either March or April 2013.

Table 2

List of Inconsistencies and Confusing Terminology in the TBPOC Report

	Page #	Confusing Terminology or Inconsistent Mixed Uses	Comments
1	ES-4 -10 -11, -12, 9,46 47,49	lower housing of shear keys S1	"housing" is inappropriate; change to " stub baseplate" or "base plate," which is used on page 27. The shear key housing refers to the top half and the shear key stub to the bottom half (See Pier E2 Shear Key Detail No. 1). DE352BJ and DE353BF uses the term "base plate."
2	ES-5	final design load of 0.68 Fu	In other places, 0.7Fu is the design load. If 0.68 is a significant figure, it should not be rounded up to 0.7. The target load by AB/Fluor was 0.7Fu in pretensioning the anchor rods for S1 and S2.
3	ES-15	17 locations where A354 grade BD ar	On p. ES-2 and p.3, the rods were referred to as at seven different locations. Table ES-1 shows 7 locations and 17 items.
4	ES-17	impose a tight tolerance on hardness	The word "tolerance" is incorrect. Change to a tight "range."
5	1	elements that have a minimum specified	The word "elements" is unnecessary and misused.
6	5	17 different types of A354 grade BD rods at seven different locations,	"17 different types" is confusing. See comments on ES-15. They are all one type, Grade BD, hot dip galvanized, in different dimensions.
7	6	Figure 2 A354 Grade BD Rod Locations	Confusing, again, because this figure shows 17 locations. The number of circles is eight (5 reds and 3 greens), not seven.
8	7	this report uses the standard term of "rod."	This definition is violated on the next page and elsewhere throughout the report.
9	8	Shear Key Anchor Rods	On p. 7, an anchor rod is defined as "threaded on one end," which is inconsistent with this title.
10	9	Ninety-six (96) high-strength steel rods	Inconsistent use of rods and anchor rods is confusing.

Table 2 (Continued -2)

	Page #	Confusing Terminology or Inconsistent Mixed Uses	Comments
11	15	test specimens taken from near the outer diameter of	(1) A rod has a diameter, not inner or outer diameter. (2) A diameter is an imaginary line, not a volume or mass that can provide a test specimen. (3) For conformance tests, the tensile specimen should have been taken at mid-radius. The results, particularly of elongation, of specimens machined from the surface layer may not be compared with the specification requirements.
12	18	with the outer diameter approaching 39 HRC	See above.
13	19	taken from near the outer diameter of each	See above.
14	25	[4] For simplicity purposes, this report uses the term "rod."	Not done consistently.
15	68	stress corrosion cracking, per guidance from Dr. Fisher	This should be "per guidance from Dr. Townsend." He, not Dr. Fisher, published the research paper that is referenced in Note 4 of ASTM A354.
16	75 ES-14	The collection of water in their support cylinders	"High strength rod guide pipe" is part of the drawing title by American Br/Fluor, Sheet No. DE325A and DE326A. "Support cylinders" may be a misnomer.

Table 3

List of Technically Erroneous or Questionable Statements in the TBPOC Report

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
1	ES-5	by which metals become brittle and fracture	Metals do not necessarily become brittle macroscopically, for example, during tensile testing, when they fracture due to hydrogen embrittlement. The embrittlement due to hydrogen in high strength steel is a localized phenomenon, in a microscopic scale. The tensile test results of the failed rods from S1 and S2 with 15% elongation satisfied the 14% minimum spec requirements.
2	ES-6	*from hydrogen that was already present and available in the rod material as they were tensioned.*	Superfluous. All hydrogen embrittlement (HE) is due to the hydrogen that was already present and available. Otherwise, no HE would occur.
3		The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement.	What is the normal susceptibility of the steel? Without defining this, this conclusion is meaningless and unacceptable.
4		The metallurgical condition of the steel was found to be less than ideal.	Nebulous statement. The term "ideal" must be defined. Otherwise, meaningless.
5		*the microstructure of the steel is inhomogeneous resulting in large difference in hard- ness from center to edge,*	For the section thickness (3-inches), the microstructure of the 4140 alloy used would be expected to be "inhomogeneous" when quenched and tempered.
6		*the material exhibits low toughness and marginal ductility.*	The tensile specimens were removed from the surface layer, not from a mid-radius location as required by ASTM F606. Besides, ductility is not a factor in HE crack initiation.
7		As used in this report, hy- drogen embrittlement is considered a short-term phenomenon	This is true only when HE is restricted to internal hydrogen embrittlement. This simplistic understanding of HE has led to a wrong conclusion of the S1 andS2 anchor rod failures, which were due to environmental hydrogen embrittlement, not due to (internal) hydrogen embrittlement.

Table 3 (Continued -2)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
*8	ES-8	High-strength steels over 150 ksi possess a metallurgical structure that can have an affinity for hydrogen.	The word "affinity" may be inappropriate. The (chemical) affinity of steel for hydrogen does not change with the strength. In fact, the affinity of iron (and steel) for hydrogen is very low as compared with that of zirconium or titanium.
9		Too much heat could cause the release of internal hydrogen	"Too much" is unnecessary. The "upquenching" effect occurs at 850ºF, the median temperature for HDG, according to Brahimi.
*10		subject the rods to less heat	Not less heat; the mechanical galvanizing does not use heat.
*11	ES-9	not uniform across the thickness of the rod and parts did not have the expected material properties.	For diameters greater than 2½ inches, the 4140 steel will not have a uniform structure "across the thickness of the rod" when quenched and tempered. "did not have the expected material properties" contradicts the previous statement that the rods satisfied the minimum tensile property requirements for ASTM A354 Grade BD.
12		desired uniform metallurgical structure and desired material properties.	The Caltrans spec had no desired structures or properties specified that were different from (or in addition to) the minimum requirements of ASTM A354 Gr. BD.
*13		the second heat treatment may have further hardened and	This is an erroneous conjecture. The final hardness and tensile strength is dependent on the tempering temperature/time, not on the number of heat treatments.
*14	ES-10	visual examinations found evidence	A visual examination may find a clue, but not evidence for "hydrogen-assisted cracks."
*15		including hydrogen-assisted cracking	Not including. The "hydrogen-assisted cracking" is the only cracking mechanism responsible for these rod failures. There are no other cracking mechanisms to account for them.
16		of ferrite and pearlite in between layers	This is not uncommon for 3 inch ϕ 4140 steel quenched and tempered.
* 17		May not have had optimal through-thickness hardenability	This is a well-established and well known fact for 4140, which is the most common low alloy steel used for high strength steel fasteners.

Table 3 (Continued - 3)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
18 *	ES-10	the presence of water may have been a contributing source of hydrogen (	Not a contributing source of hydrogen. This is the principal source of hydrogen for the S1 and S2 rod failures due to environmental HE. Otherwise, no other explanation is possible as to why the 32 failures occurred all in the bottom threads.
19		due to hydrogen embrittlement.	The S1 and S2 rods failed due to [environmental] hydrogen embrittlement, which according to the TBPOC, is the *long-term stress corrosion cracking*, the nomenclature not used in the corrosion or material science literature.
20		three conditions of susceptible material, high tensile strength and the presence of hydrogen all were present,	The high tensile strength should be "high tensile stress."
21	ES-12	on the commencement and rate of corrosion	The word "commencement" is superfluous and "rate of corrosion" is misleading. SCC/EHE can occur without visual evidence of corrosion, particularly with zinc coating.
22		The results from Tests I, II and III	Many hardness data of Tests I and II seem very odd and need verification. See a separate discussion.
23	ES-13	provide important data for further analysis	Both Tests IV and V will produce K_{ISCC}, which is hardness/strength dependent. The results will not be greatly different from those already available in the literature.
24	ES-14	maximum steel hardness	The rod surface as the hardness test location must be stipulated. This is still not done.
25 *		and through consistency	"through consistency" is not attainable in 4140, quenched and tempered, in rod diameters greater than 2½ inch ϕ.
26		2) minimum steel toughness, 3) magnetic particle testing, and 4) a time-dependent test	These tests could not have prevented the S1 and S2 anchor rod failures, which were due to the bottom threads being exposed to wetness for five years.
27 *		support cylinders may have exacerbated the embrittlement of the 2008 b	Not "exacerbated," it is the principal reason why the S1 and S2 anchor rod failed, all in the bottom threads.

Table 3 (Continued - 4)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
28 *	ES-14	The large-diameter rods were not tested	This is immaterial because the ASTM A143 test is not helpful as an HE test method for the S1 and S2 anchor rods.
29 *	ES-17	at small intervals across the diameter, ensuring homogeneous metallurgical	Taking hardness readings at small intervals across the diameter will not ensure a homogeneous metallurgical structure. What is more important is the maximum hardness at the surface.
30		test" required by ASTM F606	These tests will not be helpful for the SAS rods for detecting HE failure potentials.
31	14	• Cracks developed and grew in both rods.	The report did not mention that both rods failed in the bottom threads. Did not mention all failures occurred in the bottom threads. Did not mention any other cracks than the fracture face were found.
32 *		a number of brittle fracture mechanisms,	Not true. For low alloy steels, hydrogen embrittlement cracking is the only cracking mechanism that would show the intergranular cracking mode at room temperature.
33		almost exclusively cleavage (brittle	Not true. TBPOC's "Briefing on E2 Anchor Bolts - April 24, 2013," Slide 9, SEM 5 consists more dimples than cleavages.
34		banded nature of the microstructure i	A banded microstructure is not uncommon in commercial grades of steel, including 4140 steel, quenched and tempered.
35	15	large disparity in hardness from center to edge	This is not unusual for 4140. It was to be expected.
36		improperly heat treated.	This could have been verified; but not done.
37		mid-radius Rockwell C hardness values from 32.5 to 36.2 HRC	The hardness at the surface or thread root would be more important. What was the hardness range at the surface?
38		toughness of the steel, which was called into question by the failures.	The brittle appearance of the fracture is more due to the notch effect of the hydrogen embrittlement cracks than toughness in question.
39 *	18	to as low as 25 HRC, indicating the material	25 HRC at the surface is almost impossible. This low hardness may have been influenced by improper specimen preparation. The data need to be verified.

Table 3 (Continued - 5)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
40	19	these rods exhibit a lack of toughness.	Not an important factor in the S1 and S2 anchor rod failures.
41		individual test results outside of the specifi-	Not true.
42		grade BD material was susceptible to hy- drogen embrittlement;	Not true. Only Grade BD with high hardness is susceptible to hydrogen embrittlement.
43		The material was not homogeneous (i.e., compos	This is the way 4140 steel is. That is to be expected.
44		evidence of elongated inclusions (i.e., the	Not a significant factor.
45 *		the elasticity and distribution of the load within the mate- rial may vary;	Elasticity will not vary regardless of the hardness. Load distribution across the diameter is not affected by the hardness gradient.
46 *		no evidence of surface corrosion near	Visual examination cannot determine the corrosion of the zinc layer.
47	20	Additional Heat Treatment	As commented before, this should not have been a factor in the S1 and S2 anchor rod failures.
48	21	HE can seriously reduce ductility and load-bearing causing cracking and brittle failures at stresses below the yield stress of susceptible materials.	HE can occur without displaying reduction in ductility in tensile tests. The load-bearing capacity decreases because of hydrogen embrittlement cracks. The two are separate and different issues. "below the yield stress" is usually expressed as "below the yield strength."
49		typically occurs within days to a couple of weeks of stressing.	May be applicable only to internal hydrogen embrittlement, not to environmental hydrogen embrittlement.
50 *		High-strength steels exceeding a ten- sile strength of 150 ksi possess a metallurgical structure that has an affinity for hydroger	As commented before, the affinity of steel for hydrogen remains the same; it does not change or increase with the strength/hardness. It is the susceptibility to HE, not the affinity for hydrogen, that increases with hardness/strength.
51		that when all three conditions apply the metallurgical structure of the steel has a higher susceptibility to HE.	This is a misstatement. The susceptibility of the metallurgical structure does not change because of the other two factors.
52		[4] For simplicity purposes, this report uses the term "rod."	Another confusing footnote. In spite of this footnote and a definition of rod, several terms are used interchangeably in this report.

Table 3 (Continued - 6)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
53	26	• Has a minimum strength between 140 and 150 ksi	This is a misstatement. For Grade BD, the 140 ksi min applies to >2½ inch in diameter, not between 140 and 150 ksi.
54		A354 Grade BC 125 3	Should be A354 Grade BC 115 | 3.65.
		• Has a minimum specified tensile strength between 115 and 125 ksi	This is a misstatement. For Grade BC, the 115 ksi min applies to >2½ inch in diameter and the 125 ksi min to ¼ to 2½ , incl .
55		F1554 125 3	Should be F1554 125 | 3.4 (or 3.5).
56 *		Susceptible to hydrogen embrittlement without due care when galvanizing	Hot dip galvanizing increases the susceptibility of steel to (environmental) hydrogen embrittlement with or without "due care."
57		A354 Grade BC Less susceptible to hydrogen embrittlement	Should read "not susceptible" to to hydrogen embrittlement
58		• Would require more rods and larger connecting surfaces (than BD)	This is not entirely true. For S1 and S2, 3¼ inch Gr. BC would have provided a 98% of the clamping force of 3 inch Gr BD. The S1 and S2 base plate had enough space for 96 3¼ inch rods.
59		A722 150 3	No need for this grade unless it is guaranteed to be immune to hydrogen embrittlement in the marine atmosphere.
60	27	2nd paragraph	Not quite true. The rods on Pier E2 could have used Gr BC without altering the mass or the sizes of the anchor rods for bearings, shear keys and cap beam.
61		sole-source restrictions that discouraged	Unless the sole source materials were immune to hydrogen embrittlement, there would be no advantages of choosing A722. It would have failed in the same way as Gr BD if it had experienced the same history as the failed anchor rods. So, this lamentation is useless.
62	28	Sole-Source Restrictions	This is irrelevant because A722 rods could have failed in the same manner as the S1 and S2 rods, given the same service history including the exposure to stagnant water for five years.

Table 3 (Continued - 7)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
63 *	29	High-strength steels over 150 ksi possess a metallurgical structure that can have an affinity for hydrogen,	This statement, which is erroneous, appears five times in this report. The affinity of steel for hydrogen remains the same, at a low level, irrespective of a metallurgical structure.
64 *		increased through the application of heat or when subjected to high levels of stress.	Heat and stress would increase the diffusion rate or the mobility of hydrogen within the steel lattices, not the affinity for hydrogen.
65		Too much heat could cause the release of internal hydrogen and when encapsulated i in the zinc coating increases the risk of hydrogen embrittlement.	This occurs anyway during hot dip galvanizing, too much heat or not, or encapsulated by the zinc coating or not.
66 *		mechanical galvanization at room temp. may minimize the affinity for hydrogen	Again, the affinity of steel for hydrogen is unaffected by temperature.
67 *		may be difficult to do for most galva	Not "difficult." It is impossible.
68		tumbling threaded rods can damage the threads.	This is irrelevant. Besides, the threads can be damaged in other processes as well, including hot dip galvanizing.
69 *	32	[1] ASTM A143 describes procedures that can be followed to safeguard against the possible embrittlement of steel hot-dip galvanized after fabrication, and outlines test procedures for detecting embrittlement.	These tests will not detect hydrogen embrittlement, both internal and environmental, of 3 inch Grade BD anchor rods.
70	33	The April 2000 update of the Caltrans Bridge Design Specifications Manual prohibits the galvanization of A354 grade BD rods due to hydrogen embrittlement problems.	In this context, the hydrogen embrittlement problems include the "*long-term stress corrosion cracking*" as defined by the TBPOC.
71		hot-dip galvanizing on A354 grade BD could make the steel more susceptible to hydrogen embrittle- ment.	These tests will not detect hydrogen embrittlement of 3 inch Grade BD anchor rods.
72 *		ASTM A143 provides guidance on the "Standar	ASTM A143 is not helpful for detecting hydrogen embrittlement in Gr. BD rods.

Table 3 (Continued - 8)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
73 *	34	, the initial specifications for the SAS Bridge contracts required the rods to be mechanically galvanized -	This is utterly amazing that the spec writers and reviewers did not know the basic processes involved in mechanical galvanizing when ASTM B695 would have to be referenced and it describes the tumbling process. A surprising show of limited knowledge on hydrogen embrittlement/*long-term stress corrosion cracking*.
74 *	37	Caltrans staff raised concerns about "strain age embrittlement" a	Indication of lack of basic metallurgical knowledge.
75 *	43	the second heat treatment may have further hardened and strengthened the material and contributed to the rods' susceptibility to hydrogen embrittlement.	Illogical and unfounded conjecture. A second heat treatment, when properly done, would be perfectly acceptable.
76 *		the metallurgical structure was not uniform across the thickness of the rod and parts did not have the expected material properties.	This is exactly what is to be expected of 3 or 4 inch diameter 4140 steel that was quenched and tempered.
77 *		This indicates the steel production etc.	This is a wrong interpretation for lack of metallurgical knowledge.
78	44	high-strength rods with appropriate fabrication control measures is 31 HRC to 35 HRC.	This new hardness range is meaningless without specifying the hardness test location. If this hardness range applies to R/2, the surface hardness can be 39 HRC, which can cause HE/SCC.
79		QC and QA testing of high-strength rods per the SAS contract were performed in accordance with hardness measurements taken at R/2	Not completely true. Many suppliers reported hardness test results for the surface and the "core."
80	45	but the presence of water may have been a contributing source of hydrogen contamination in the rods (	This is the most significant factor that can explain why all 32 failed in the bottom threads and none in the top threads. It is the source of the hydrogen for these failures.
81	51	cross-sectional hardness survey.	Many of these data show M shaped profiles, which do not make sense and would require a metallurgical evaluation.
82	53	Table 10 Post-Heat Treatment QC/QA Mechanical	Without citing the specimen locations, e.g., surface layer or R/2, these data are meaningless.

Table 3 (Continued - 9)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
83	53	159 | 139 | 16 | 51 | 34	159 ksi tensile strength does not correspond to 34 HRC.
84		148 | 125 | 19 | 57 | 37	148 ksi TS and 37 HRC are inconsistent.
85 *		156/161 | 132/140 | 14/16 | 48/48 | 39/39	Inconsistent and 39/39 HRC Ave improbable.
86	54	ASTM D = ¼"–2½" 140 (min) | 115 (min) 31 - 39	These requirements are wrong for the size group, ¼ - 2½ inch. The correct requirements are 150/130/33 – 39.
87	55	These extracted rods were examined extensively	Unless the extract rods were selected from those with high hardness and unless the rods were subjected to MT or PT, this test is meaningless.
88		The 2008 material failed at a tension level substantially lower than the actual yield strength of the rods,	This is incorrect. The 2008 rods failed at 0.68Fu, which is 95 ksi, which is 80% of the minimum specified yield strength (115 ksi).
89 *		which is evidence of hydrogen embrittlement and lack of toughness.	Not true. Toughness is not a significant factor in HE.
90 *		Given these material differences in the 2010 rods	These comparisons are unfair. The 2008 rod results were obtained from the failed rods due to HE because of high hardness and hydrogen charged and the 2010 rods that were tested had lower hardness and were not charged with hydrogen.
91 *	57	What Is Stress Corrosion Cracking? is the growth of cracks in a corrosive environment,	Stress corrosion cracking (SCC) does not occur in all corrosive environments; it requires a specific species, which in this case is hydrogen.
92		If highly stressed steel is not protected, accelerated stress corrosion may occur, which could lead to stress corrosion cracking.	Unintelligible. There is no difference in meaning between stress corrosion and stress corrosion cracking.
93 *		ships and offshore structures, where history has witnessed some catastrophic failures.	Ships and offshore structures have not failed due to SCC.
94	58	His research found that electroplated and and hot-dipped zinc coatings decrease the resistance to stress corrosion cracking in direct levels of stress intensities.	"His" should be replaced by "Townsend's." Otherwise, the credit for this research goes to Fisher. "in direct levels of stress intensities." does not make sense.

Table 3 (Continued -10)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
95 *	58	Stress intensity is a function of the diameter of the rod and the tension the rod	This is incorrect as stated and would need a better description of the stress intensity factor.
96 *	63	Chemical analysis at three locations of the same cross section	This will not provide any useful data about chemical segregation. One would be sufficient.
97 *	66	These test results also provide conclusive evidence that the cause of the high-strength rod failures observed in March 2013 from short-term hydrogen embrittlement	This is the wrong interpretation. It completely ignores the effects of the bottom threads having been exposed to wetness for five years prior to pretensioning. As such, these are SCC as defined by the TBPOC, not IHE failures. This is the most egregious error of this report.
98	67	Items #2 - #17	Item #1 should have been included.
99		Plot Each Rod on the Townsend SCC Curve Using Individual Critical Stress Intensity & Hardness at Surface Values	This was not done for items 2 – 5 before deciding to replace them.
100	68	exhibit better metallurgical uniformity and improved toughness.	Not completely true. Some data were wrong as will be shown later.
101 *	70	Table 13	The microstructure column is inconsistent throughout. Item #1 is the only item that is listed as not being martensitic with 36.9 – 38.2 HRC. Item #2 is "essentially martensitic" with 29 – 39.3 HRC. So is Item #7 with 25.1 – 38.9 HRC. This item has rolled threads, which would show a cold worked structure. It cannot be essentially martensitic with 25.1 HRC.
102 *	71	Mode of fracture and Toughness CVN Item #1 Brittle 13 - 14 (min - max) Item #7 Ductile 13 – 18.5 (min - max) Item #11 Ductile Insufficient sample length to perform test	Again, inconsistent throughout the columns. The distinction between brittle and ductile seems arbitrary. Should have shown % shear, not ductile vs brittle. #11is classified as "ductile" without data to support it.
103	74	The root cause of the failures is higher than normal susceptibility of the steel to hydrogen em- brittlement."	Again, meaningless without defining the "normal susceptibility." Conventionally, the susceptibility of most steels to hydrogen embrittlement is normally zero.

Table 3 (Continued - 11)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
104	75	6. 1) maximum steel hardness and through consistency, 2) minimum steel toughness, 3) magnetic particle testing, and 4) a time-dependent test of the rods under tension	Largely irrelevant except for the maximum surface hardness.
105		The collection of water in their support cylinders	This was the most significant factor in the S1 and S2 anchor rod failures.
106		8. ASTM 143 required a hydrogen embrittlement test.	Should be ASTM A143, not ASTM 143. This test is irrelevant to Gr BD rods.
107	78	Stress corrosion cracking occurs over years or decades of sustained tension and is based on the commencement and rate of corrosion.	This is an erroneous statement. See Ref. 18. One of the curious aspects of stress corrosion cracking is the wide difference in time required for failure, which varies from a matter of minutes to many years. SCC is unrelated to rates of general corrosion.
108		if so, when cracking may occur.	There is no way to predict when or if SCC or EHE may occur for any particular anchor rod.
109	79	Replace After Opening, 2, 3, and 4	This does not make sense. See a separate discussion.
110		7. PWS Anchor Rods Dehumidification	State the maximum relative humidity.
111		Item #7 PWS anchor rods	Must consider the effects of cold rolled threads on HE cracking.
112 *	81	The *in-situ* surface hardness of these rods varies widely from 25 to 39 HRC,	Need to establish the hardness at the root of cold rolled threads and the effect of cold working on HE susceptibility.
113		Item #7 - 3.5" (PWS) Anchor Rods: PWS Anchor Rods are housed inside a water-tight, dehumidified chamber	The chamber needs to be air-tight, not water-tight, with air-lock doors.
114		Item #8 - 4" diameter Tower Saddle Tie Rods: a water-tight, dehumidified chamber so	
115		Item #8 - 4" diameter Tower Saddle Tie Rods: hardness of these rods (from 35 to 38 HRC) a water-tight, dehumidified chamber so	Need to establish the hardness at the root of cold rolled threads and the effect of cold working on HE susceptibility The chamber needs to be air-tight, not water-tight, with air-lock doors.
116	82	Item #12 - 3" diameter Tower Anchor Rods: water-tight, dehumidified chamber so	The chamber needs to be air-tight, not water-tight, with air-lock doors.

Table 3 (Continued - 12)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
117	82	Item #13 - 4" diameter Tower Anchor Rods: water-tight, dehumidified chamber so	The chamber needs to be air-tight, not water-tight, with air-lock doors.
118 *	83	impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring, thereby ensuring homogeneous metallurgical structure.	A homogeneous structure is not possible whether taking hardness readings at small intervals or not.
119		hydrogen embrittlement "pull test" required by ASTM F606 and the Townsend and Raymond	The ASTM F606 pull test has nothing to do with SCC susceptibility.
120	86	The Seismic Peer Review Panel has provided comments on the report,	The panel overlooked a lot of errors.
121 *	88	Charpy V-Notch Test An impact test … is absorbed in fracture is calculated by	Not calculated. Should read "by reading the needle location on a dial or read off a digital display."
122	89	iron oxide, which is commonly known as rust	Iron rust comprises hydrated iron oxides and iron hydroxide.
123		where reliance on coatings may be impractical.	Should read, "may be insufficient," not impractical.
124	90	Grade BD .	Unnecessary repeat of ASTM A354 Grade BD on page 88.
125		Grade BD rods are 140 ksi for 25/8-	Should write "2 5/8-inch" or "2⅝-inch."
126	92	The Raymond Test	Not included whereas the Townsend Test is included in 10. Glossary of Terms.
127		SSPC-SP 10 A standard established by the	Should include, "SSPC stands for Steel Structures Painting Council, precursor to the Society for Protective Coatings."
128 *	93	Strain-age Embrittlement steel becomes very brittle in areas of high stress when exposed to elevated temperatures.	Not in areas of high stress. Should read, "in cold worked areas…."
129 *		When the steel has incurred enough stress due to strain-aging, it can become embrittled	This was copied from an AGA site; but it is a misstatement. Strain aging does not "incur stress" or due to the stress. As the name indicates, the strain aging is due to the strain, not due to the stress, in the material.
130 *		High-strength steels over 150 ksi possess a metal- lurgical structure that has an affinity for hydrogen, which is increased through the application of heat or when subjected to high levels of stress.	This is erroneous. The HE susceptibility is at maximum at room temperature and falls off with temperature.

Table 3 (Continued - 13)

(*: Errors, indicative of lack of basic metallurgical knowledge)

	Page #	Erroneous or Questionable Statements	Comments
131 *	93	Townsend Test An accelerated test to determine the longer-term susceptibility of a material to stress corrosion cracking.	The Townsend test determines KI_{SCC} or σ_{SCC} using full size rod specimens, which is different from determining the long-term susceptibility of a material to SCC.
132 *		Vacuum Degassing A process where molten order to remove excess hydrogen or carbon.	Vacuum Degassing does not remove carbon. Vacuum oxygen degassing (VOD) can.
133 *		Vacuum degassing to remove carbon r	Erroneous
134 *		By removing the carbon, the metals become more ductile, or easily shaped and	Erroneous
135 *	94	Zinc Electroplating Using the electroplating process changes the chemical and physical prop- erties of a metal.	Erroneous. Electroplating can change the chemical and physical properties of only the surface, not the substrate metal itself. This item should be removed because Zinc Electroplating does not appear in the report text.

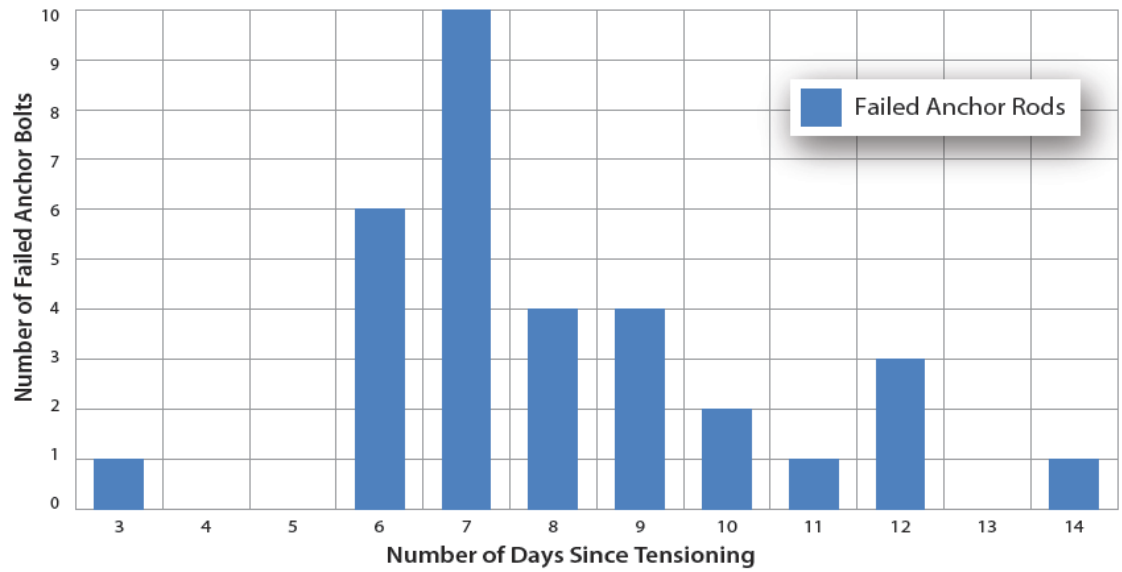
Table 4

List of Technical Questions Regarding the HDG Grade BD Rods on the SAS Bridge

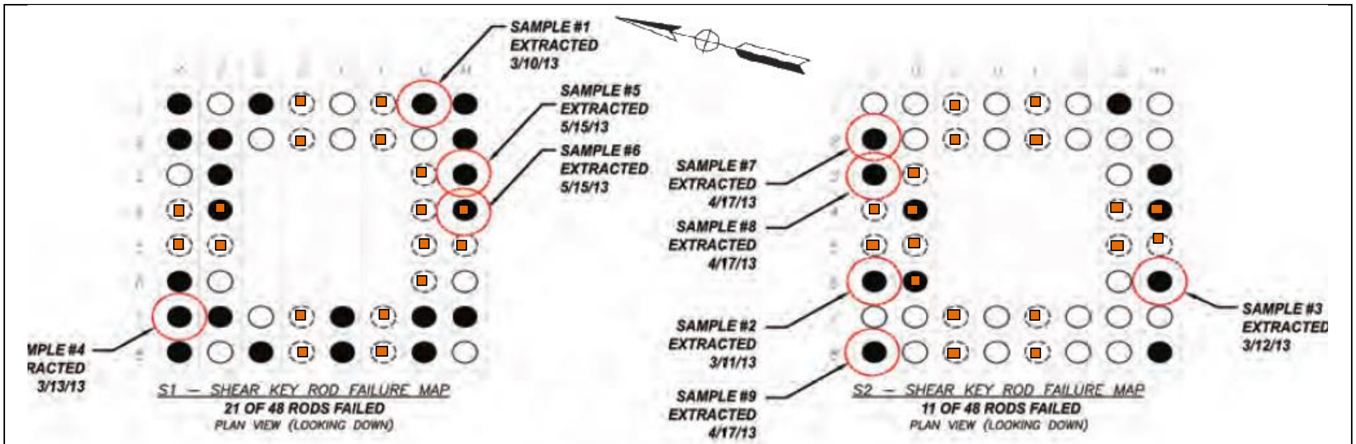
	Questions	Refer to
1	If "As used in this report, hydrogen embrittlement is considered a short-term phenomenon that occurs in metals, including high-strength steel," if "The longer-term concern is whether the remaining A354 grade BD rods are susceptible to stress corrosion cracking and," and if "The risk of near-term hydrogen embrittlement has passed. The potential for longer-term stress corrosion cracking can be managed safely and effectively," then, do the "hydrogen embrittlement (HE)" or "short-term HE" and the "*long-term stress corrosion cracking*" as used in the TBPOC report mean internal hydrogen embrittlement (IHE) and environmental hydrogen embrittlement (EHE) cracking, respectively?	p.ES-64 p.ES-12 p.ES-15
2	If " These test results also provide conclusive evidence that the cause of the high-strength rod failures observed in March 2013 from short-term hydrogen embrittlement is isolated to the shear key S1 and S2 anchor rods at the top of Pier E2 manufactured in 2008," and the "short-term HE" is the same as IHE, why is Dyson not held accountable for these S1 and S2 anchor rod failures?	p.66
3	If the 32 anchor rod failures of S1 and S2 shear keys were due to "short-term HE" (or IHE), why did all of them fail in the bottom threads and none in the top threads?	
4	If "*The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement*," what is the "normal susceptibility" to hydrogen embrittlement (HE) for high strength steel bolting material such as ASTM A354 Grade BD and how is it determined?	p.20
5	Do the Grade BD rods with rolled threads meet the intent of the heat treatment requirement of ASTM A354?	
6	What are the effects of forming the threads by cold rolling on environmental hydrogen embrittlement (*or long-term stress corrosion cracking*) failures of Grade BD rods?	
7	How can the Townsend Test data be used to assess the long term performance of the anchor rods on the SAS Bridge?	p.93
8	What are the effects of hardness traverse curves that are M shaped (see Fig. 26) such as for 4 inch Tower Base anchor rods on EHE (or *long-term SCC*) susceptibility?	File E17
9	Are there any possibilities of the bottom threads of the tower base anchor rods (Items #12 and #13) getting wet and develop EHE failures, particularly if they are connected to a cathodic protection system or exposed to stray currents, during the life of the SAS Bridge?	

Table 4 (Continued - 2)

<table>
<tr><th></th><th>Questions</th><th>Refer to</th></tr>
<tr><td>10</td><td>If PWS Anchor Rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, what are the criteria of dehumidification and controls? An air-tight, not water-tight, chamber, with air-lock doors for access, is required for effective dehumidification of the air inside the chamber.</td><td>p.81, 82</td></tr>
<tr><td>11</td><td>What effects the toughness of metal as measured by CVN tests have on the HE susceptibility? Provide original research paper references to support the claims that the low CVN toughness contributed to the shear key anchor rod failures..</td><td></td></tr>
<tr><td>12</td><td>What is the technical justification for replacing the entire anchor rods, 740 rods, for Items #2, 3, 4, and 11.</td><td>p.79</td></tr>
<tr><td>13</td><td>If Further the 2010 material properties were substantially better than the 2008 material with homogenous microstructure and improved toughness," why is it necessary to replace the entire "2010 rods"?</td><td>p.55</td></tr>
<tr><td>14</td><td>FHWA's Greg Assessment tool uses the following six categories, including average HRC, average TS, and average CVN.
<table>
<tr><th colspan="6">Table 2: Risk Category Weighting Factors</th></tr>
<tr><th>Environment and Access</th><th>Applied Tension</th><th>Ave. Rockwell Hardness</th><th>Redundancy</th><th>Ave. Tensile Strength</th><th>Ave. Charpy Toughness</th></tr>
<tr><td>2.5</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>2.0</td><td>2.0</td><td>2.0</td><td>1.5</td><td>1.5</td><td>1.5</td></tr>
<tr><td>1.5</td><td>1.5</td><td>1.5</td><td>1.0</td><td>1.25</td><td>1.25</td></tr>
<tr><td>1.0</td><td>1.0</td><td>1.0</td><td>0.5</td><td>0.75</td><td>0.75</td></tr>
</table>
High strength steel bolt/rod failures due to HE (IHE and EHE or short-term HE and long-term SCC) are determined by the properties of individual bolts/rods, not affected by average data of a lot, item, or group. Isn't the premise of using average data an incorrect approach?</td><td rowspan="4">FHWA Report Appen-dix B</td></tr>
<tr><td>15</td><td>Why does the Ave CVN have the same "Weighting Factors" as for the Ave TS? Provide original research reference papers to support these factors.</td></tr>
<tr><td>16</td><td>TS relates to HRC approximately linearly. Why do Average HRC values have higher "Weighting Factors" than the Average TS?</td></tr>
<tr><td>17</td><td>Providing the TS and the HRC have about the same effects on the susceptibility of high strength steel to HE, these two categories together would have a "doubling up" effect of the same property when the "Weighting Factors" were summed up. Why not simply assign higher "Weighting Factors" for HRC and drop the TS?</td></tr>
<tr><td>18</td><td>What are technical references that can support the methodology of this assessment tool in the open literature?</td><td></td></tr>
</table>



(a) Shear key (S1 and S2) anchor rod failure histogram



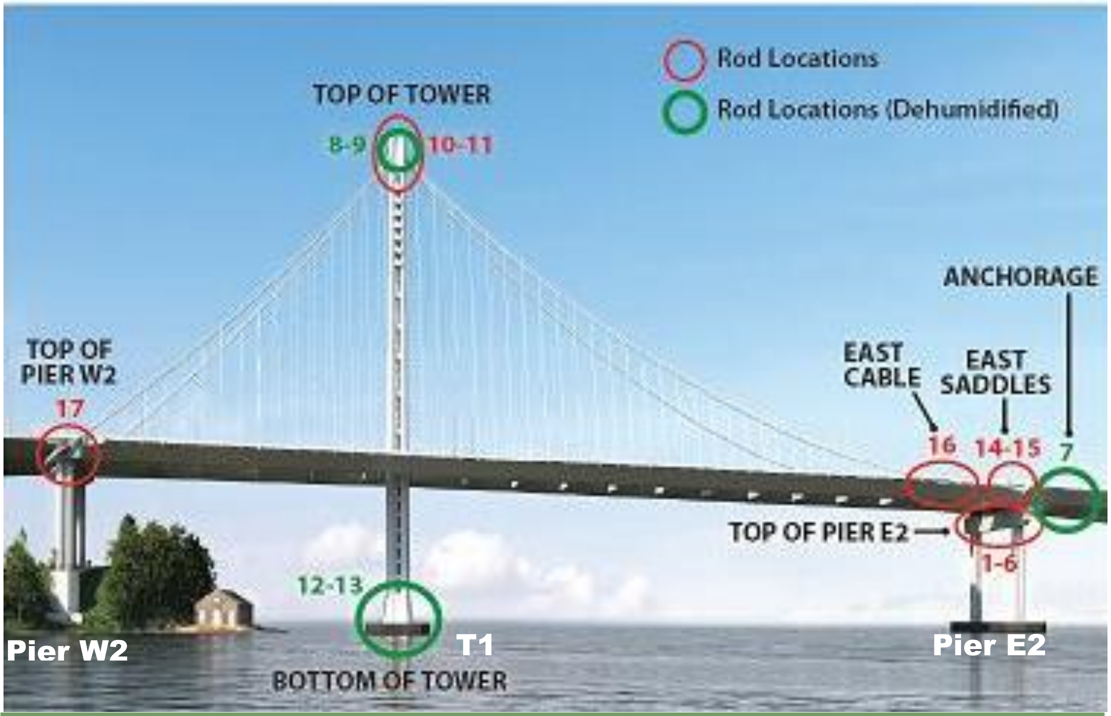
● Failed rods	○ L1 30 each, 17' long	L2 18 each, 10' long

(b) Anchor rod maps for Shear Keys S1 (left) and S2 (right)

Figure 1 (a) A bar chart showing the number of S1 and S2 Shear Key anchor rod failures vs days after pretensioning. The total number of anchor rods failed in 14 days was 32. (b) Anchor rod location maps for Shear Keys S1 and S2.

	Shear Key S1		Shear Key S2	
	L1 (17' long) HT #644914*	L2 (10' long) HT #644912*	L1 (17' long) HT #644914	L2 (10' long) HT #644912
No of 3" ϕ Gr. BD rods	30	18	30	18
No. of rods failed	19	2	8	3
No. of failed rods extracted	3	1	5	0
No of rods examined for Metallurgical Failure Analysis	1 (S1G1)	0	2** (S2A6,S2H6)	0

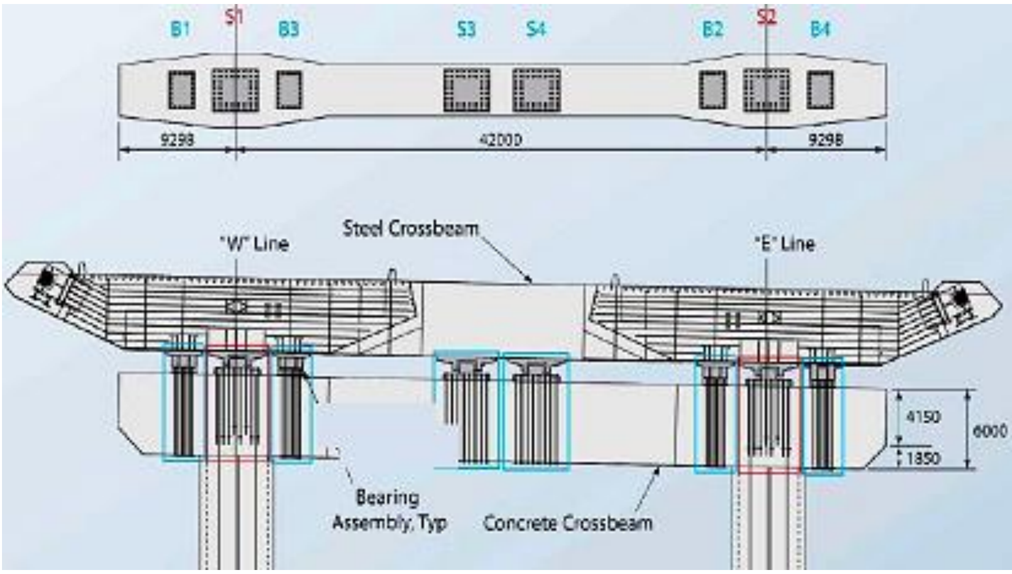
*Caltrans Report No: CMI-000016, 8/27/2008. **S2H6 was limited to a visual examination only.



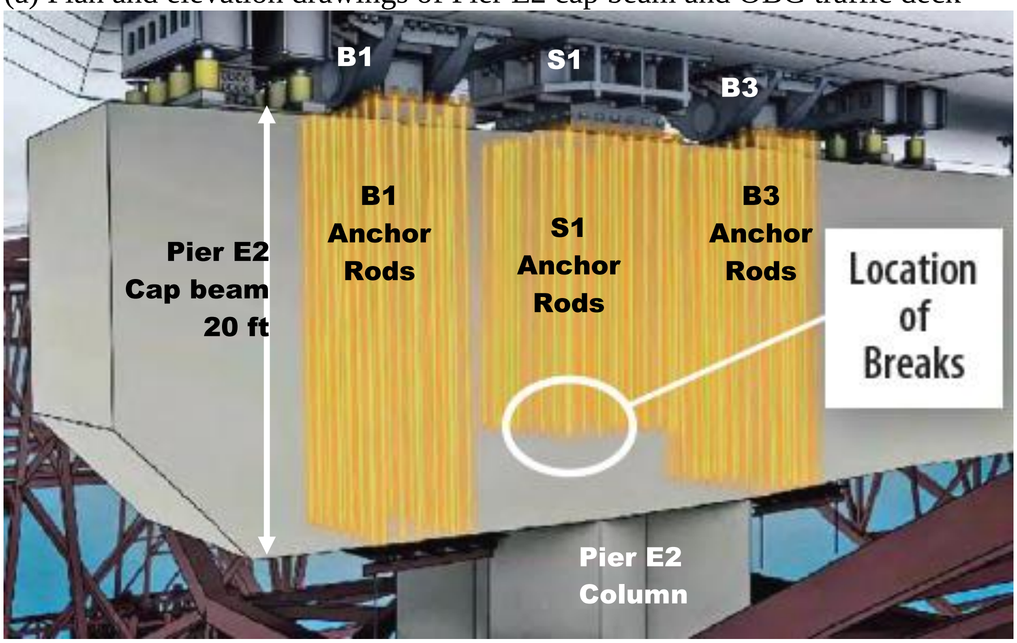
Item No.	Location	Component	Quantity Installed	Diameter (in)	Length (ft)	Tension (fraction of Fu*)
1	Top of Pier E2	Shear Key Anchor Rods (2008)	96	3	10-17	0.7
2		Bearing & Shear Key Anchor Rods	192	3	22-23	0.7
3		Shear Key Rods (top)	320	3	2-4.5	0.7
4		Bearing Rods (top)	224	2	4	0.7
5		Bearing Assembly	96	1	2.5	0.6
6		Bearing Retainer Ring Plate Assembly	336	1	0.2	0.4
7	Anchorage	Parallel Wire Strand (PWS) Anchor Rods	274	3.5	28-32	0.3
8	Top of Tower	Saddle Tie Rods	25	4	6-18	0.7
9		Saddle Turned Rods	108	3	1.5-2	0.5
10		Saddle Grillage	90	3	1	0.1
11		Outrigger Boom	4	3	2	0.1
12	Bottom of Tower	Tower Anchor Rods (Type 1)	388	3	26	0.5
13		Tower Anchor Rods (Type 2)	36	4	26	0.4
14	East Saddles	East Saddle Anchor Rods	32	2	3	0.1
15		East Saddle Tie Rods	18	3	5	0.2
16	East Cable	Cable Band Anchor Rods	24	3	10-11	0.2
17	Top of Pier W2	Bikepath Anchor Rods	43	1.2	1.5	TBD**
		TOTAL QUANTITY	2,306			

*Fu = Design-specified minimum ultimate tensile strength. Numbers rounded to the nearest tenth.
**Details for bike path support frame being redesigned to improve consistency with other design features of SAS.

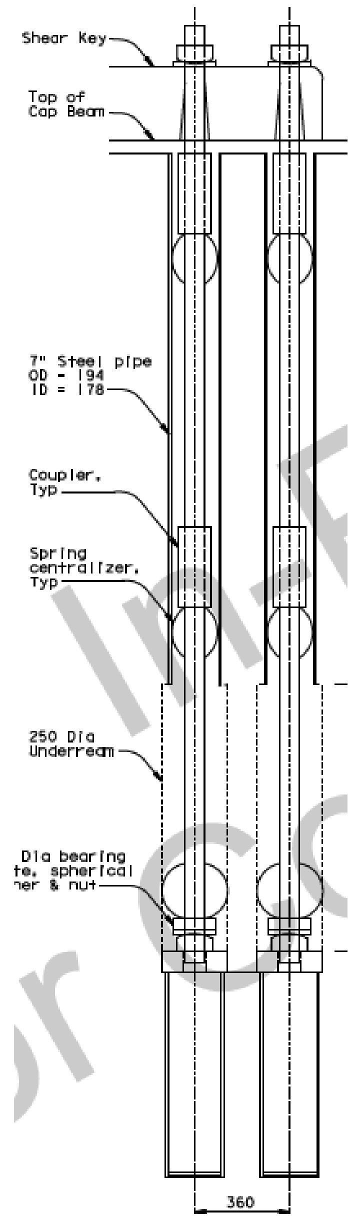
Figure 2 Identification of ASTM A354 Grade BD rods on the SAS Bridge.



(a) Plan and elevation drawings of Pier E2 cap beam and OBG traffic deck

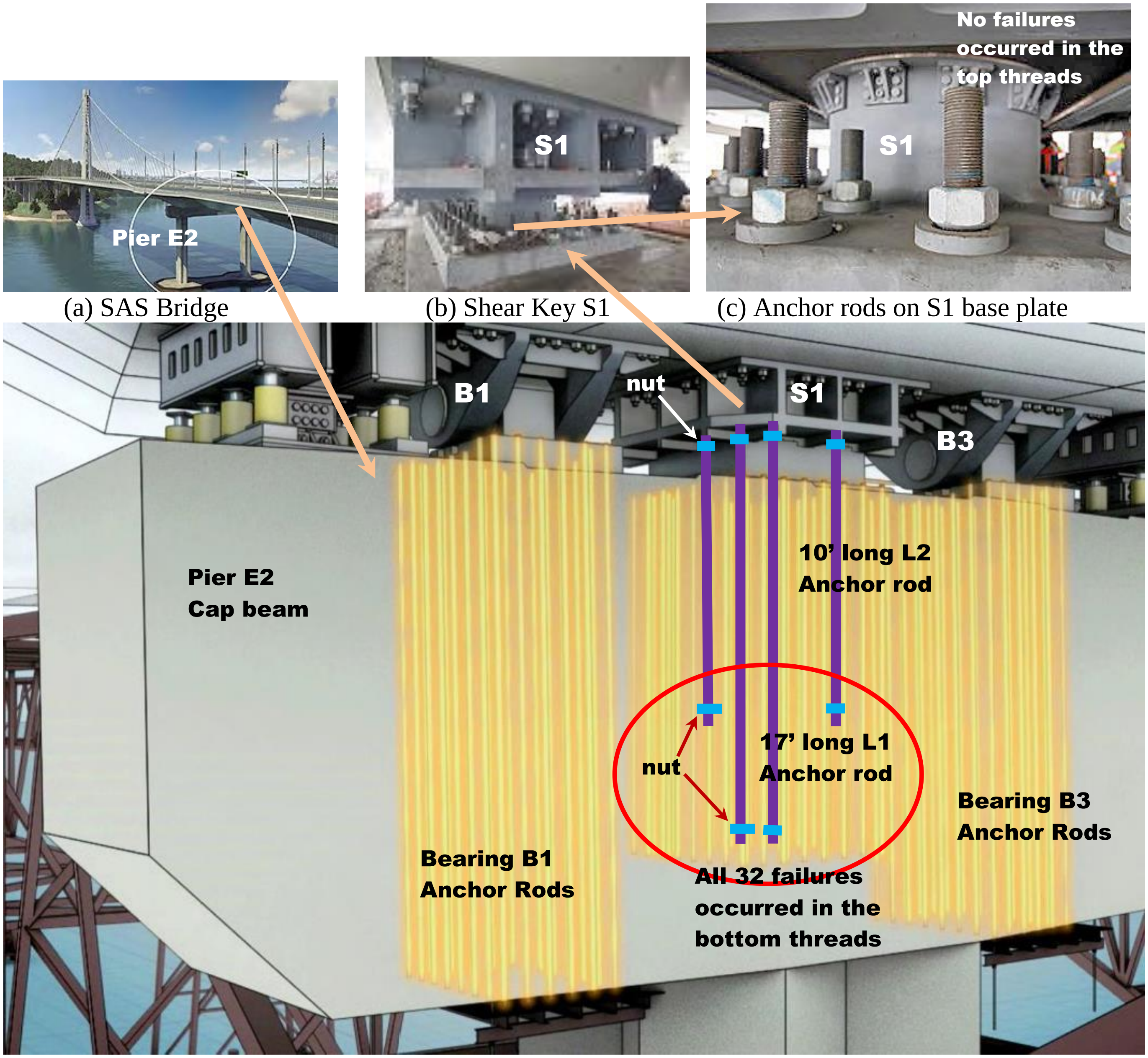


(b) Anchor rod locations for Shear Key S1 and Bearings B1 and B3



(c) Anchor rod detail

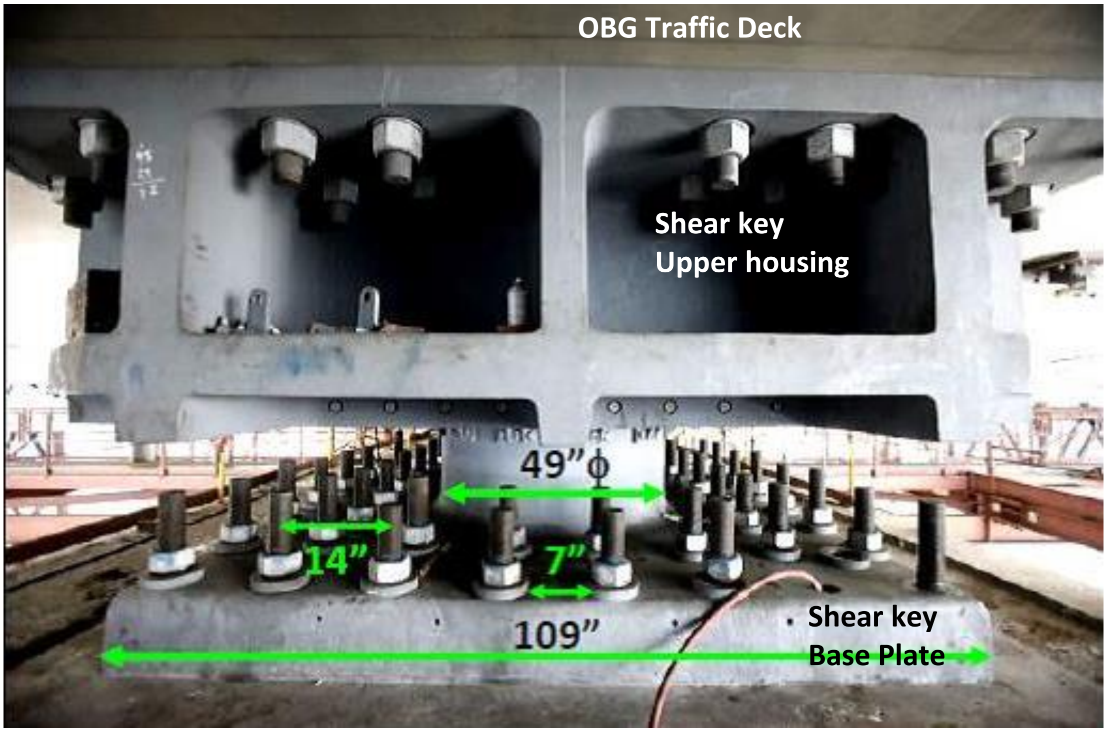
Figure 3 (a) Locations of Shear Keys S1 – S4 and Bearings B1 – B4 between the Pier E2 cap beam and the OBG (orthotropic box girder) traffic decks. (b) Anchor rod locations. Shear Keys S1 and S2 each had 48 anchor rods. 32 anchor rods failed all in the bottom threads within two weeks of pretensioning. (c) Anchor rod details for Shear Keys S1 and S2.



(a) SAS Bridge (b) Shear Key S1 (c) Anchor rods on S1 base plate

(d) The cap beam of Pier E2 with the anchor rod failure location illustrated

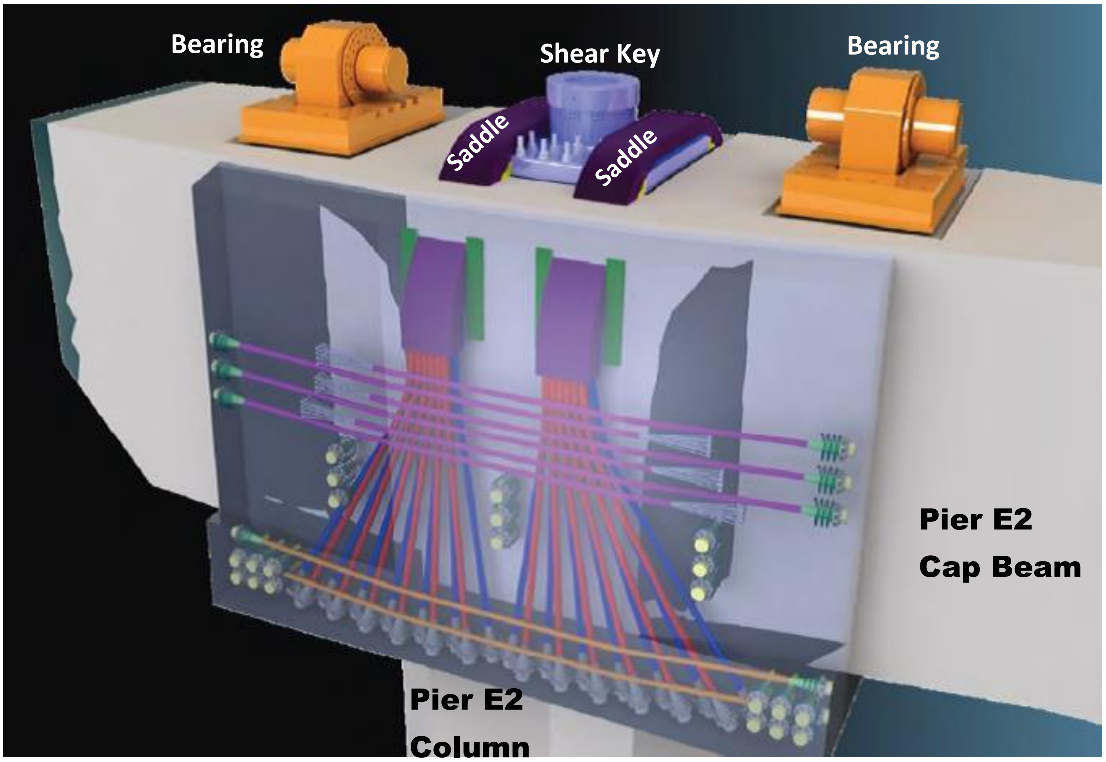
Figure 4 Illustration of the bottom threads of the L1 and L2 anchor rods as the failure location for Shear Keys S1 and S2 in March 2013. The 32 anchor rod failures consist of 21 failures in S1 and 11 failures in S2.



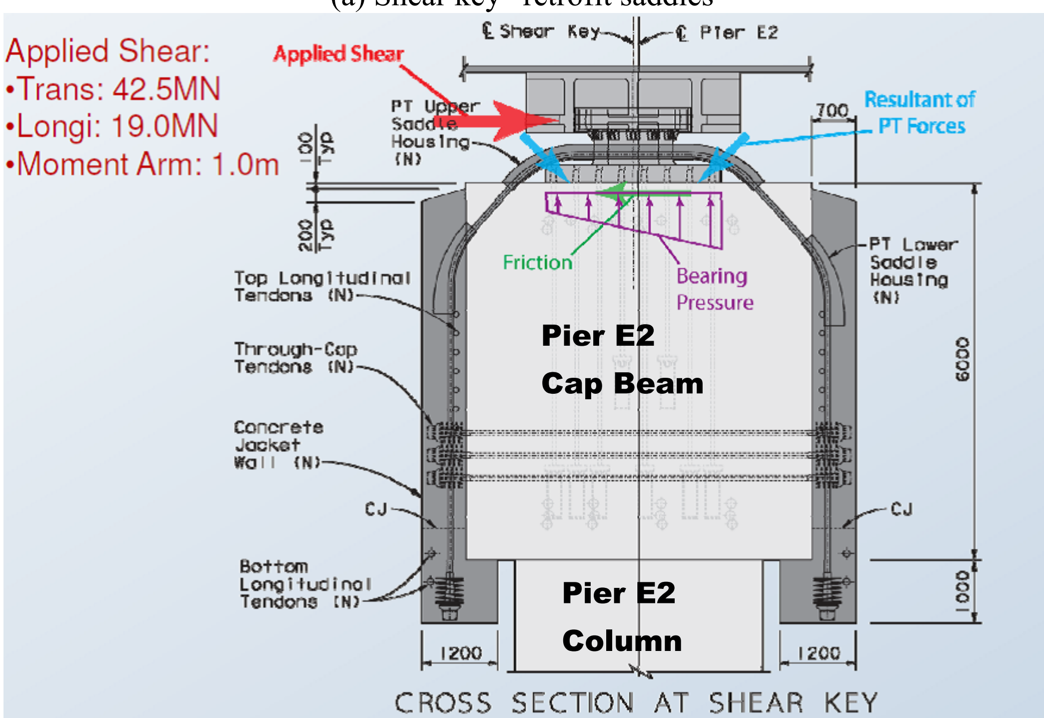
(a) Anchor rod lay out for shear key base plate

(b) A failed 3 -4UNC ASTM A354 Grade BD anchor rod

Figure 5 (a) Anchor rod lay out for the shear key base plate. The 3-inch anchor rods are 10 to 14 inches apart. The spherical washers are 7 inches in diameter. The shear key base plate, 109 x 109 x 10.8", can accommodate 3¼ inch Grade BC rods in lieu of 3 inch Grade BD rods for Shear Keys S1 and S2. The minimum tensile strength required is 816.5 kips for 3¼ - 4UNC Grade BC rods and 835 kips for 3 – 4UNC Grade BD rods. The former is 98% of the latter.
(b) One of shear key anchor rods that failed.

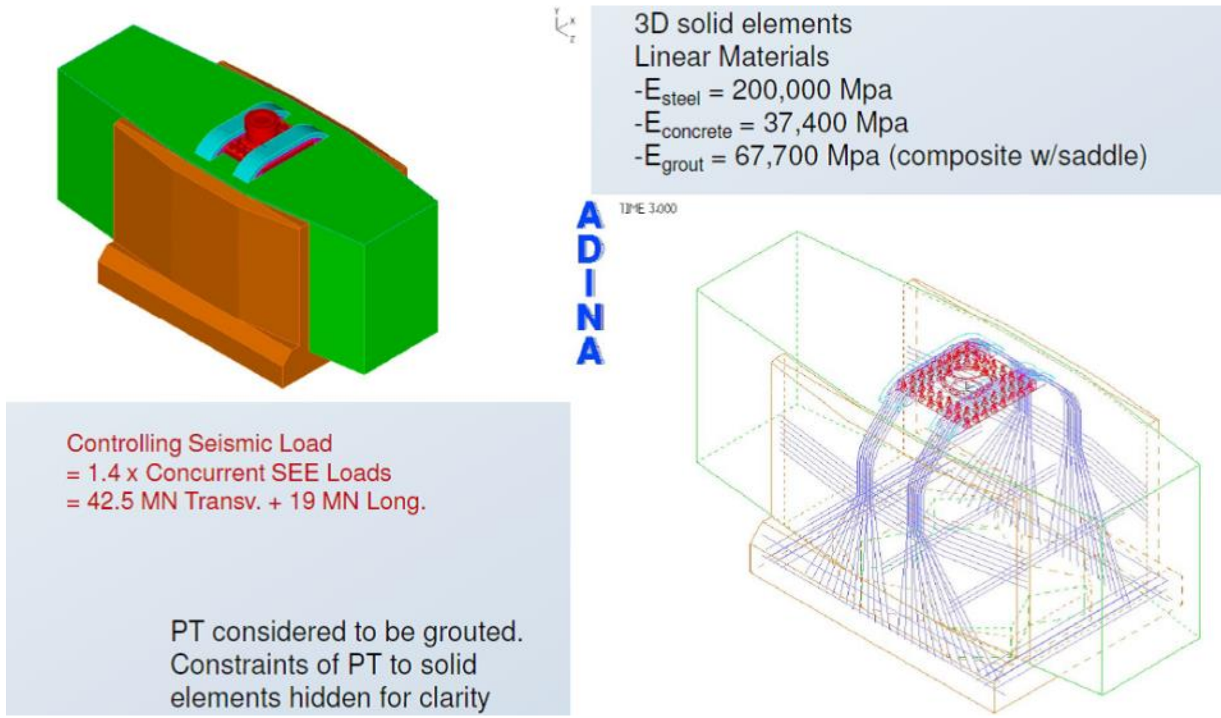


(a) Shear key “retrofit saddles”

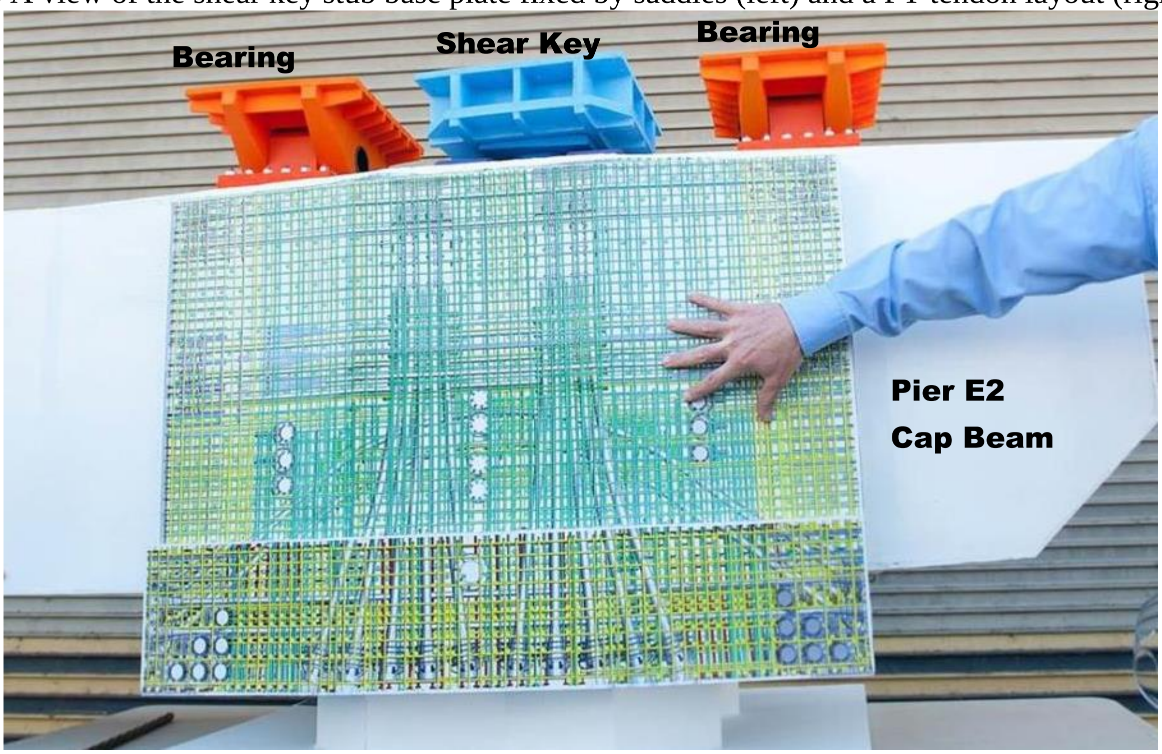


(b) Vertical sectional view of the saddle and post tension (PT) tendons encased in concrete jackets

Figure 6 (a) Saddles will replace the clamping force of the anchor rods for the Shear Keys S1 and S2.
(b) Post tension (PT) tendons will wrap the shear key base plate, be grouted and anchored to the cap beam, and be encased in a concrete jacket wall on each side of the cap beam.



(a) A view of the shear key stub base plate fixed by saddles (left) and a PT tendon layout (right)



(b) Shear key PT tendons and rebars

Figure 7 (a) The reinforced concrete jackets that will encase the saddle PT tendons. (b) Model of PT tendons and rebars to hold down the saddles over the shear key base plate.

(a) Preparation of the shear key base plate for saddle placement

(b) Rebars and PT tendons for holding the saddles down to the E2 cap beam

Figure 8 (a) A shear key base plate being prepared to receive saddles by machining corners and attaching a triangular add-on. (b) Placement of rebars and PT tendon grout cans for holding down the saddles over the shear key base plate.

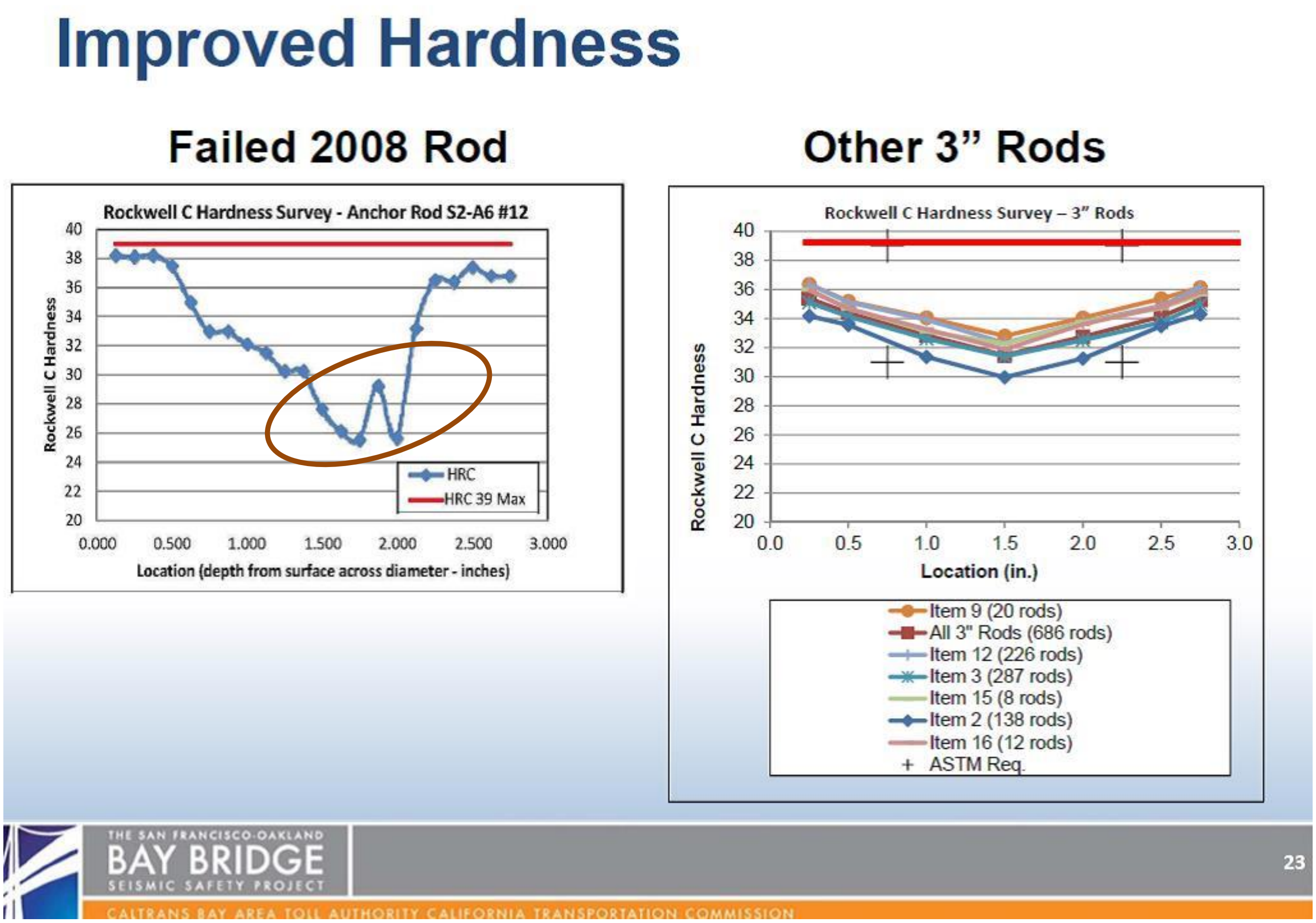


Figure 9 A comparison between (left) a hardness traverse data from a single anchor rod that failed due to HE and (right) average hardness traverse data of many rods. This is not a proper comparison to support "improved hardness" for the "other 3" rods." Individual rods among the latter had surface hardness higher than the average data shown by the graph for the "other 3" rods."

Furthermore, the hardness traverse at left may have been obtained from a specimen that was improperly prepared. That is, "hard surface grinding" of the specimen surface may have tempered the local area, lowering the hardness to around 25.5 HRC from 30 HRC. Thus, the hardness data encircled may be erroneous.

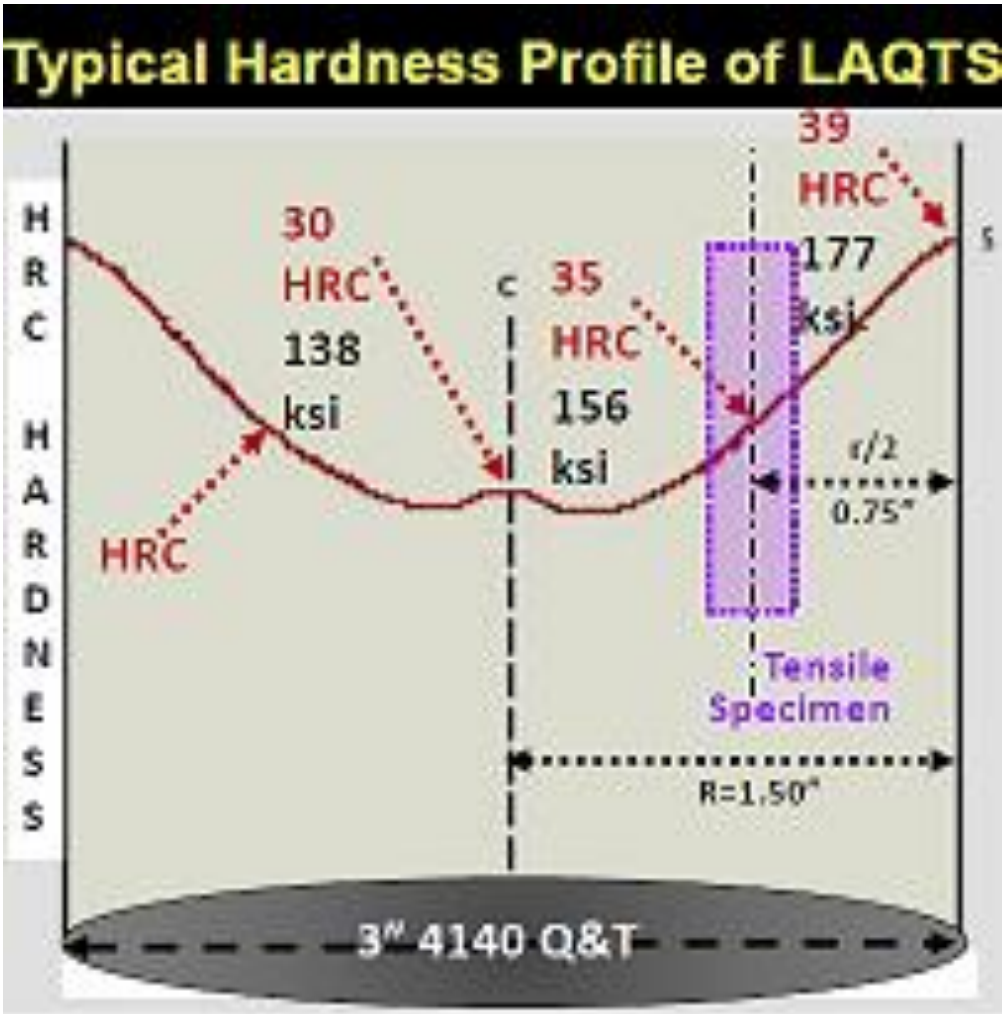


Figure 10 Typical hardness traverse profile for low alloy steel, quenched and tempered. The HRC data are actual lab test data from a 3 inch round 4140 steel, quenched and tempered at 1025ºF.

*LAQTS – low alloy quenched and tempered steel

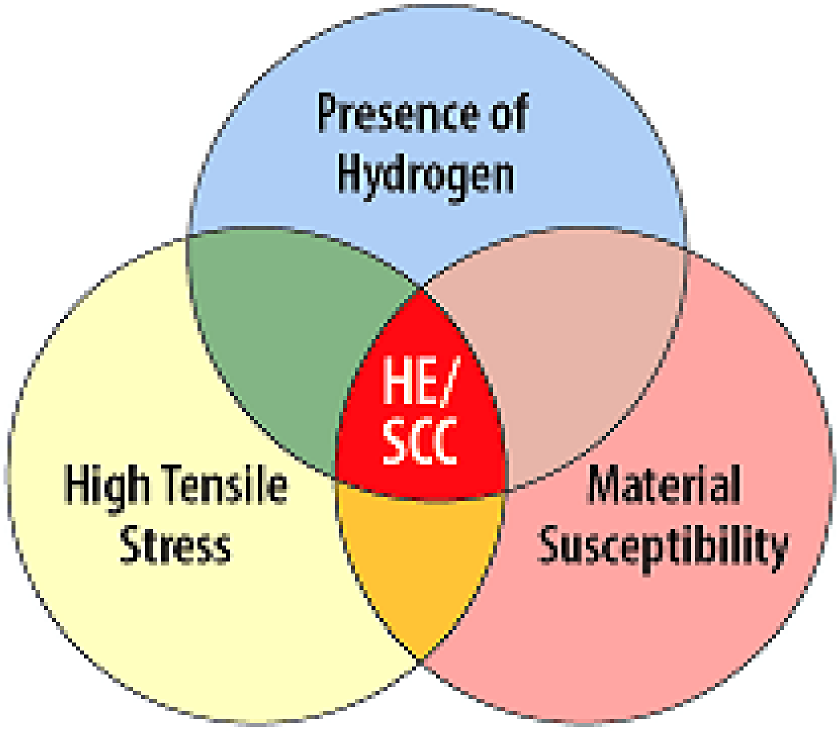


Figure 11 The three conditions for hydrogen embrittlement (HE) and stress corrosion cracking (SCC) (from the TBPOC report, p. 21).

> The accompanying Venn diagram shows that when all three conditions apply (i.e., the presence of hydrogen, high tensile stress and a susceptible material), the metallurgical structure of the steel has a higher susceptibility to HE. The diagram also shows that these same conditions can cause a related phenomenon known as Stress Corrosion Cracking (SCC), which will be addressed later in this report.

The above statement from the TBPOC report is erroneous because the susceptibility of a material to HE does not become "higher" when the material has met the three conditions. The "susceptibility to HE" remains the same. When the three conditions have been satisfied, the probability of HE failure would be "higher."

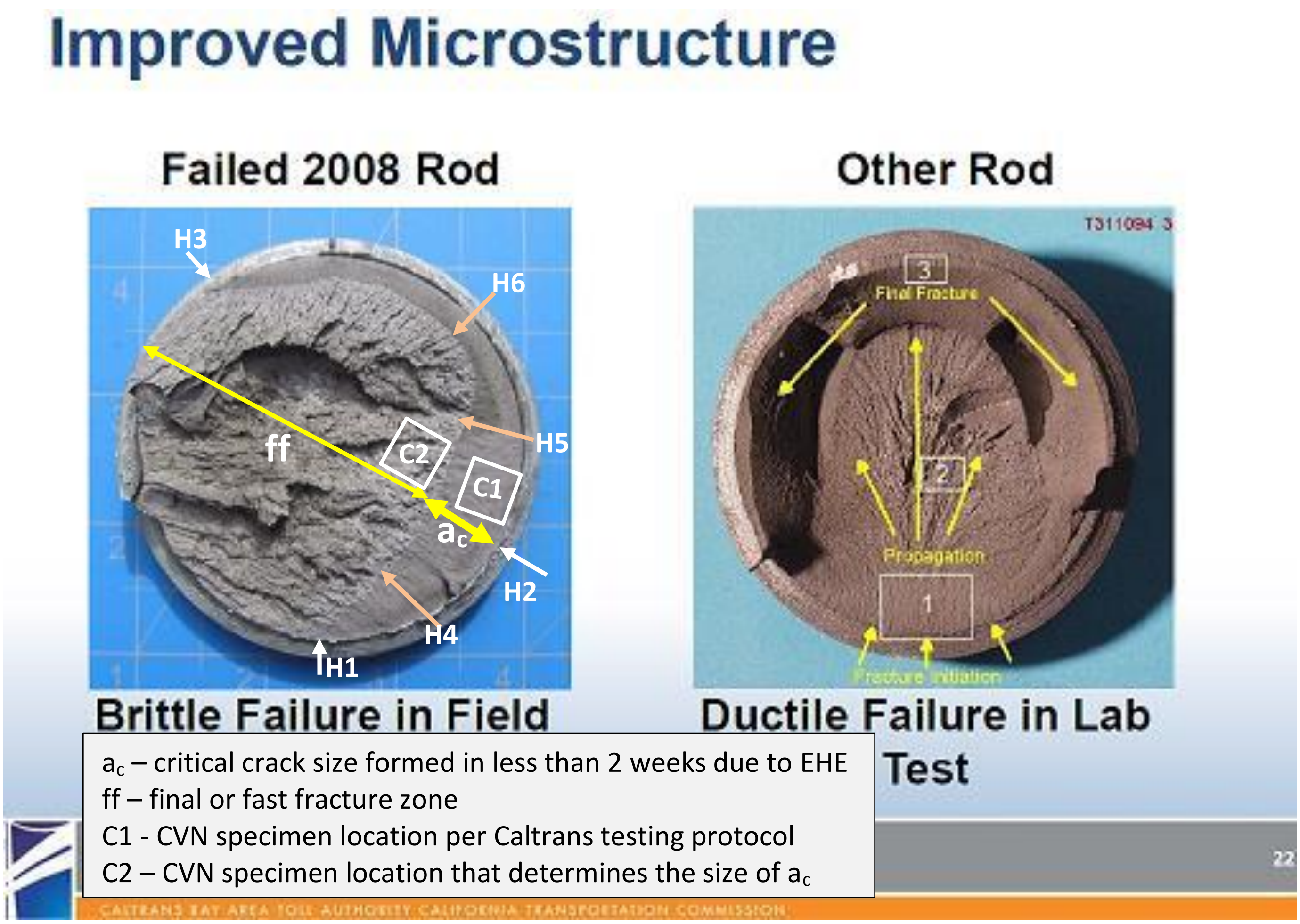
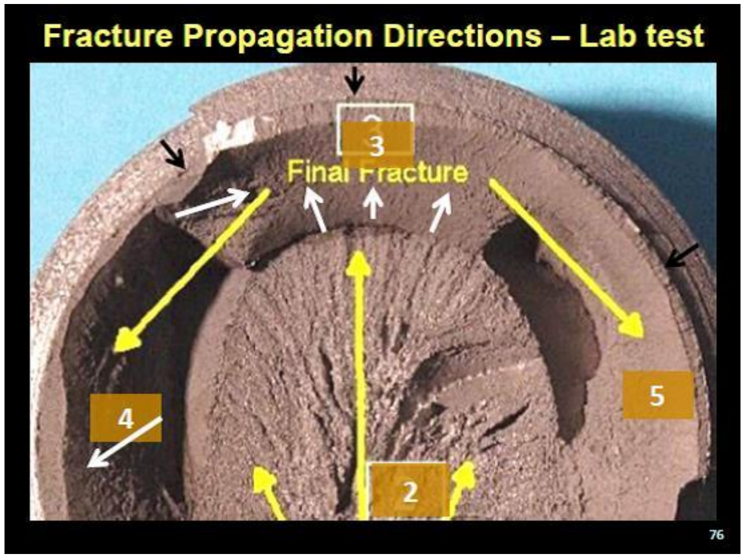


Figure 12 An example of blooper slides presented by the Caltrans Director during the July 10, 2013 BATA Briefing. The two fractures were produced under different load conditions and may not be used as evidence for "Improved Microstructure" of the "Other Rod." The top two yellow arrows in the "Ductile Failure in Lab Test" are wrong if they were drawn there to indicate the direction of crack propagation.[103]

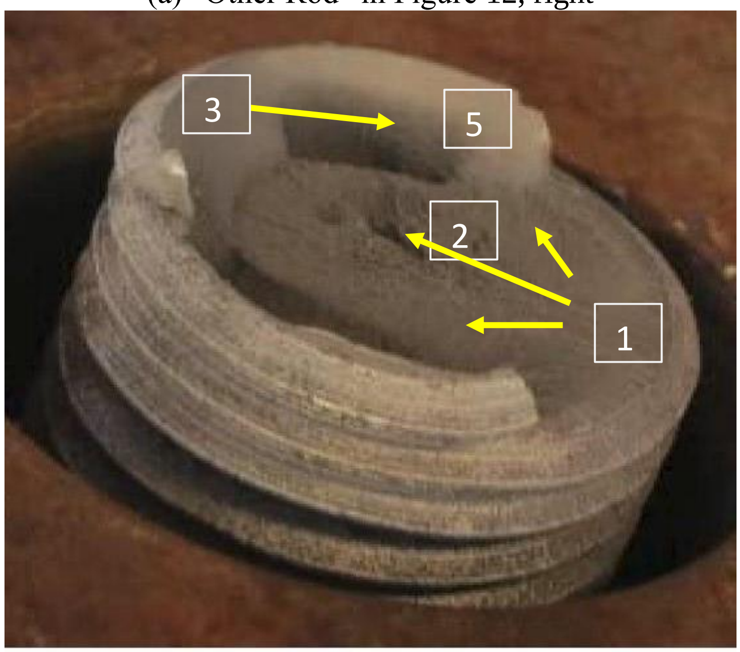
The following persons were present at this briefing and watched this slide and listened to the Caltrans Director's talk or blooper.

Three members of the TBPOC
Three member Project Management Team
Three member Seismic Safety Review Panel
Caltrans Chief Bridge Designer
California Division Administrator of the FHWA

[103] http://mtc.ca.gov/pdf/7-10-13_Briefing_on_Bay_Bridge_Bolts_final.pdf, Slide 22..



(a) "Other Rod" in Figure 12, right



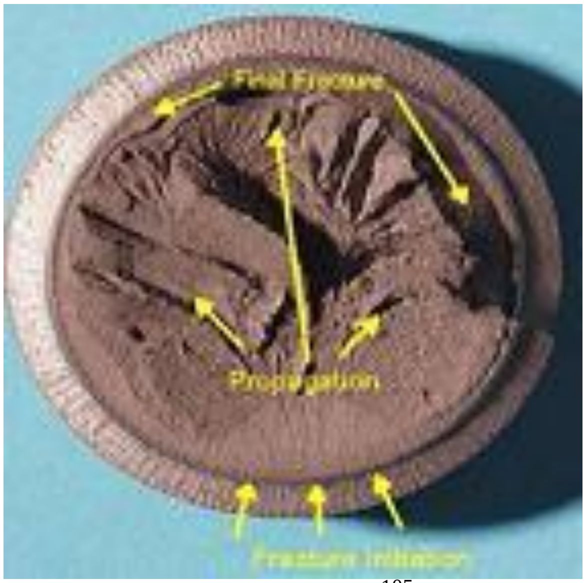
(b) SAMPLE 3-III-1: 3" SHEAR KEY TOP BOLT - TEST III

Figure 13 (a) An enlarged view of the fracture face of the "Ductile Failure in Lab Test" in Figure 12, right. A continuous fracture face as implied by the yellow arrows from "3" will not form the sharp "cliffs," which are a visual proof that the two yellow arrows are wrong as crack propagation direction indicators.

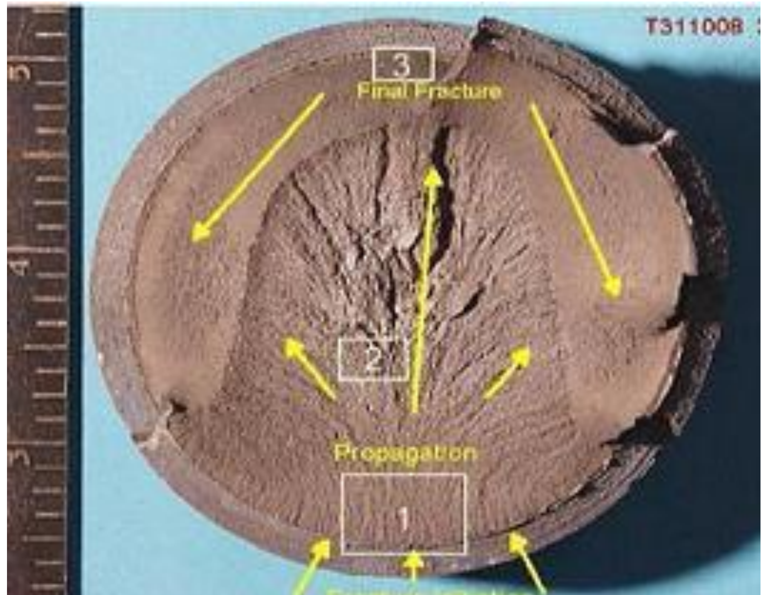
The black arrows point to a narrow flat fracture band along the thread root, which is not part of the shear lip, marked 3, 4, and 5. The white arrows point to the direction of crack propagation in the shear lip.

(b) The fracture face of the same specimen as in (a) from File E17, [104] showing that the fracture propagation from 3 to 5 cannot occur as indicated by the top yellow arrow.

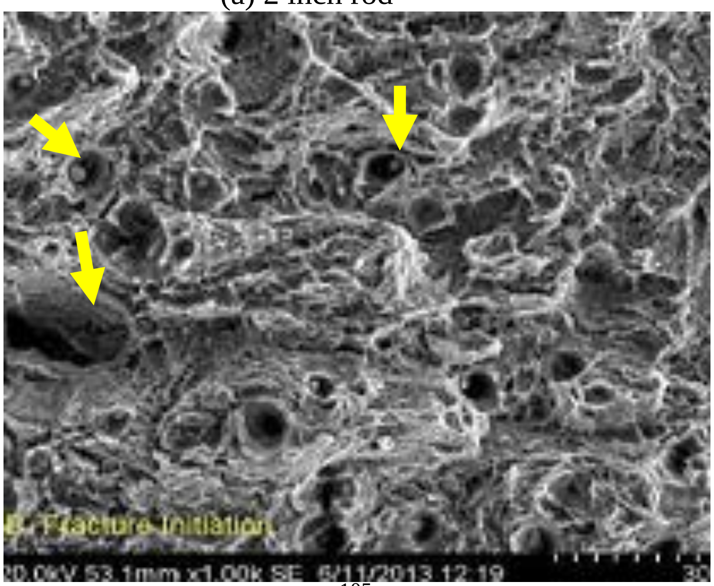
[104] http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_E_Rod_Project_Binders/E17.pdf



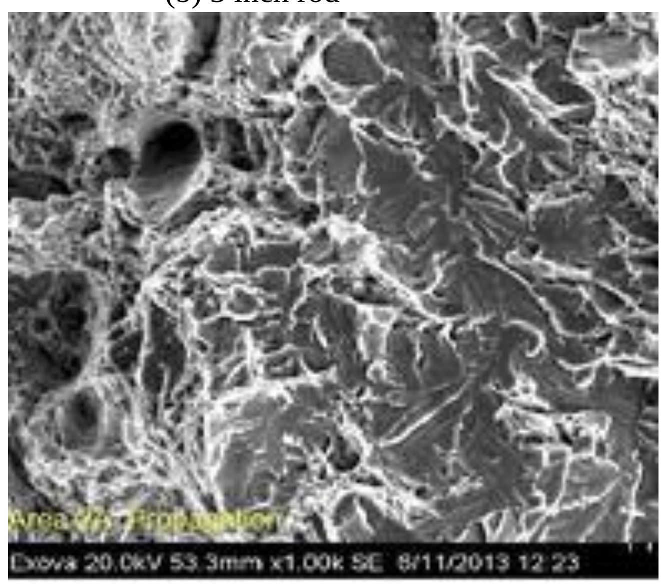
(a) 2 inch rod[105]



(b) 3 inch rod[105]



(c)[105]



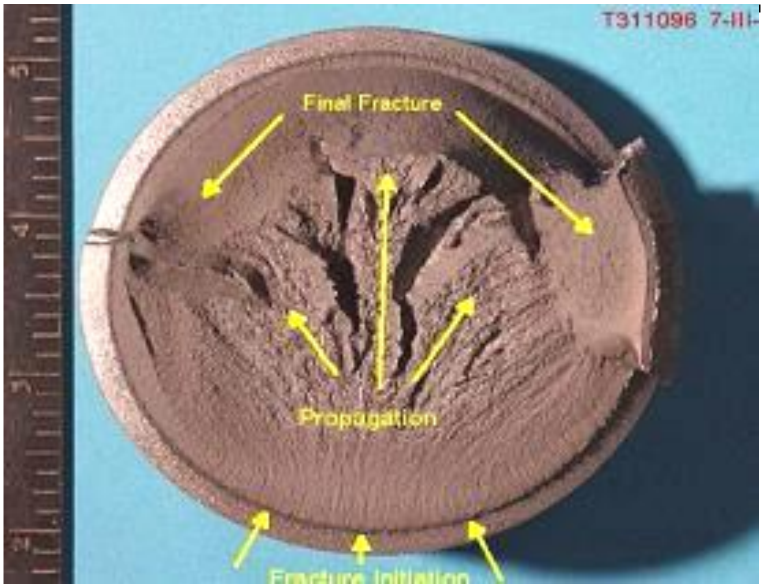
(d)

Figure 14 (a) & (b) More examples of 2 inch and 3 inch anchor rod full size tensile test fracture fracture faces. The top two yellow arrows are wrong. (c) & (d) Scanning electron fractographs of areas 1 and 2, respectively, in (b). (c) consists entirely of dimpled fractures. Large holes usually form around inclusions. (d) consists of 50:50 dimples and cleavages. Dimples are associated with ductile fractures in steel; cleavages with brittle fractures. The fractograph of (d) is a good example of what looks like a brittle fracture macroscopically is not all brittle microscopically.

“Dimples” are not known as or described as “cup and cone features.” The former is a fracture mode description in a microscopic scale and the latter in a macroscopic scale.

105 The caption of this fractograph in File E17 is as follows:

> Fracture initiation area shows dimples or cup and cone features typical of ductile fracture. Ductile fractures in the origin area usually indicates tensile overload.



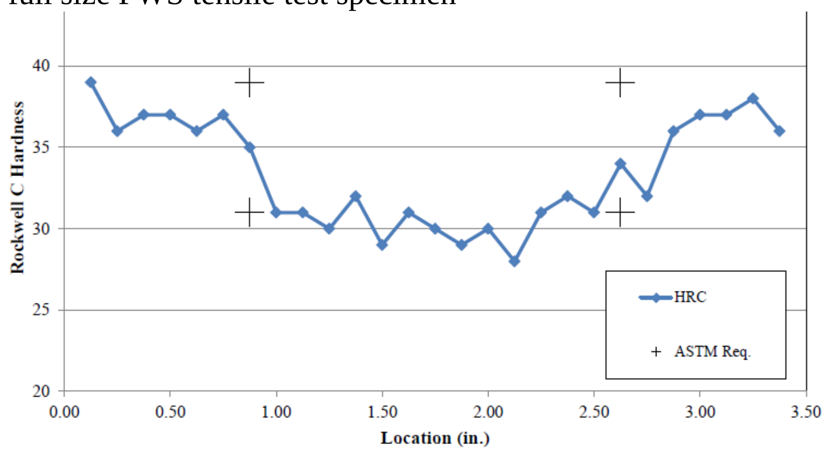
(a) Fracture face of a full size PWS tensile test specimen

Figure 15

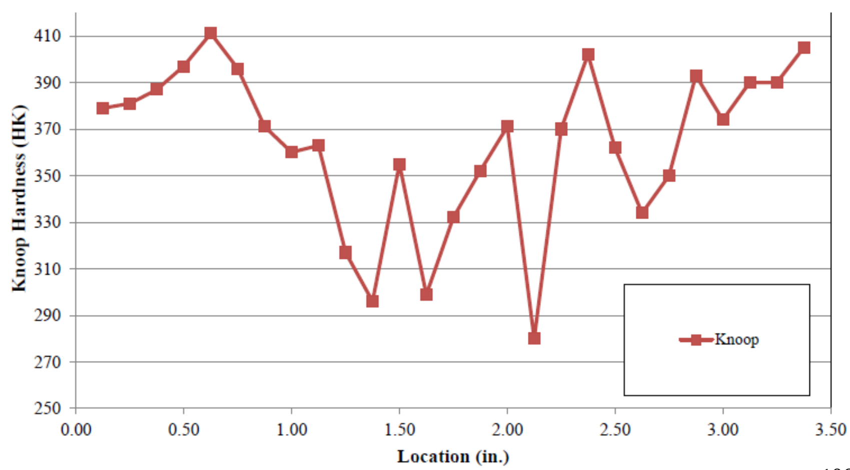
(a) The fracture face of a full size PWS (Parallel Wire Strands - main cable) anchor rod tensile test specimen. The top two yellow arrows are wrong.

(b) & (c) HRC and HK hardness traverse curves for PWS anchor rod specimens. (No load was given for the Knoop microhardness data.)

The fracture appearance as well as the HK data in (c) indicate this was not one the 219 PWS anchor rods with rolled threads.



(b) HRC hardness traverse for a PWS anchor rod sample



(c) HK (micro) hardness traverse for a PWS anchor rod sample[106]

[106] No applied load was shown for the HK data throughout File E17.

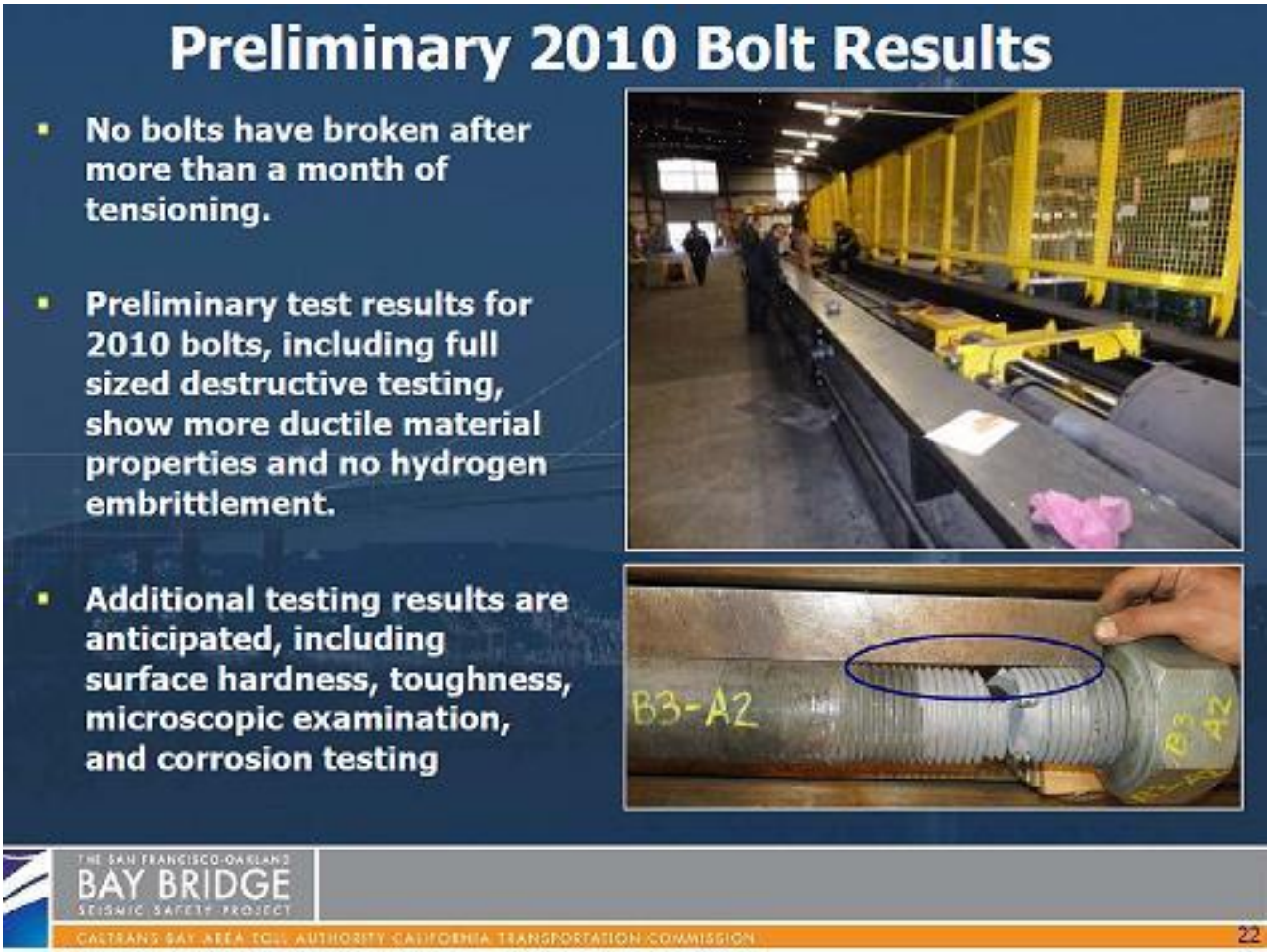


Figure 16 A full size tensile test, presented at the May 8, 2013 BATA Briefing. The circle on the bottom photograph marks the fracture location of Specimen B3-A2, which the Caltrans Director presented as "Ductile Failure in Lab Test" in Figure 12.

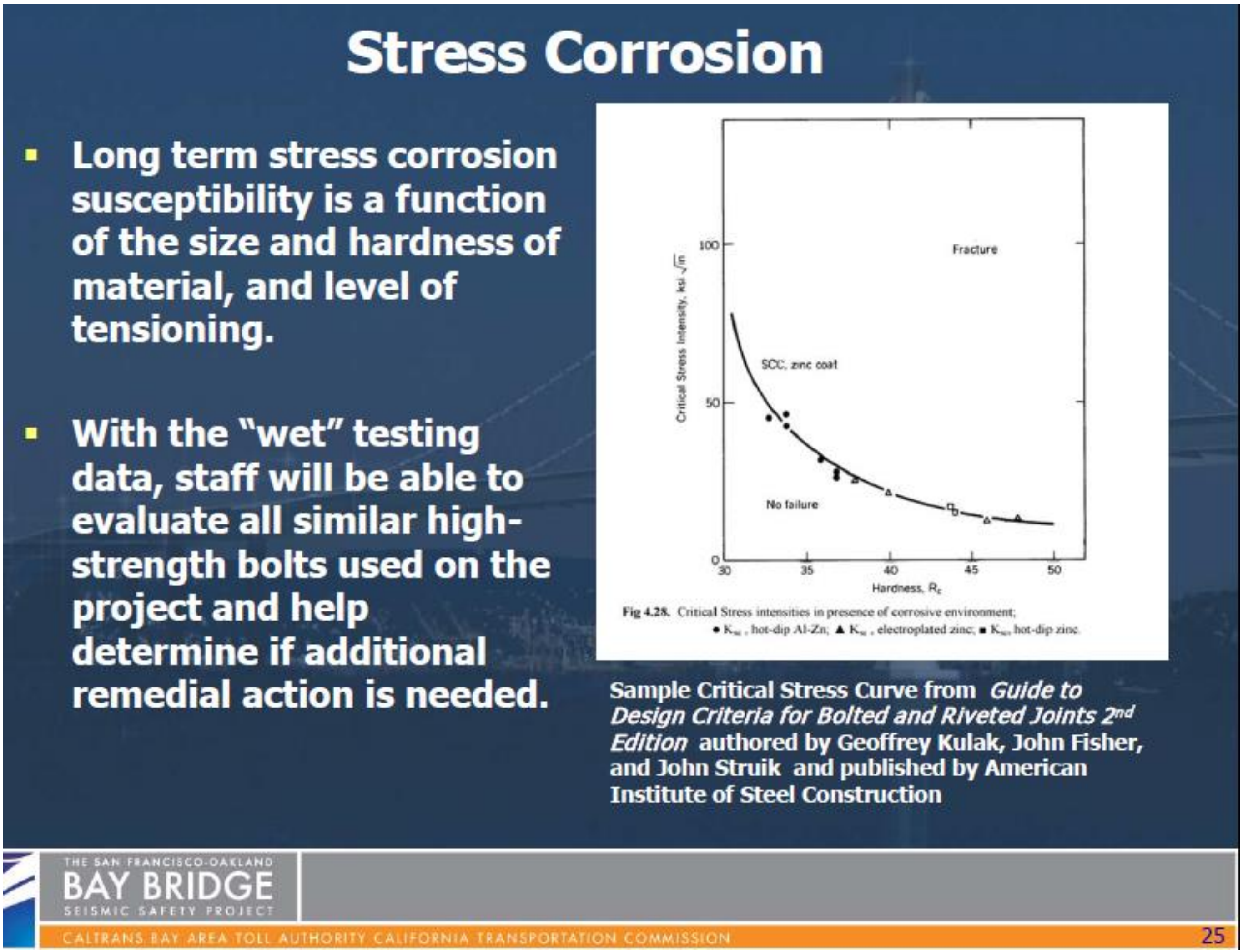


Figure 17 Critical stress intensity for stress corrosion cracking vs. hardness, presented at the May 8, 2013 BATA Briefing. The above graph is part of a graph that was originally published by H. Townsend in 1975 in the Metallurgical Transactions. Fisher introduced errors in notations when he "borrowed" the graph from the Townsend paper. The open triangles and the open squares in the lower part of the curve are supposed to be solid triangles and solid squares as indicated by the notations of the graph.

The graph in the above slide is labeled, "Sample Critical Stress Curve from …" This is wrong. A critical stress is related to but not the same as a critical stress intensity (or critical stress intensity factor). The label should have been "Sample Critical Stress Intensity Curve from …"

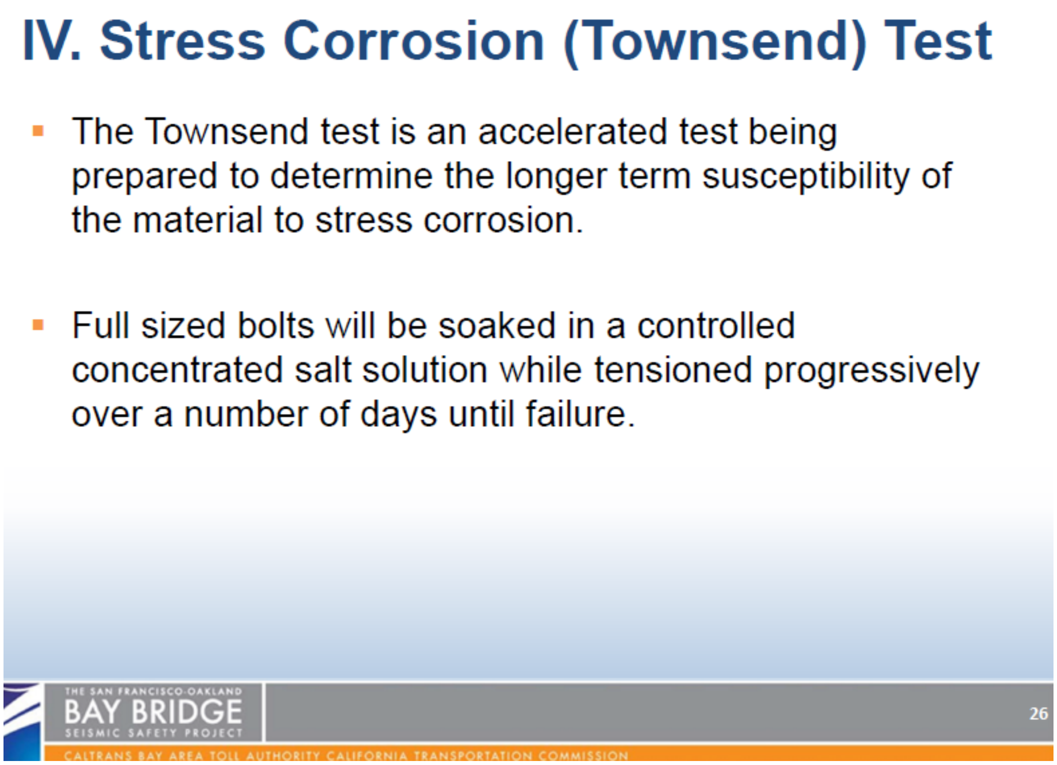


Figure 18 A wrong description of the Townsend Test at the May 8, 2013 BATA Briefing. The Townsend test is an incremental step loading (ISL) test of specimens (full size rods in this case) in an aerated solution of 3.5% NaCl at room temperature with no imposed external potential to determine the critical stress intensity for environmental hydrogen embrittlement, KI_{EHE}, KI_{SCC}, or a threshold stress, σ_{TH}. It does not determine the “long-term susceptibility of the material to stress corrosion.”

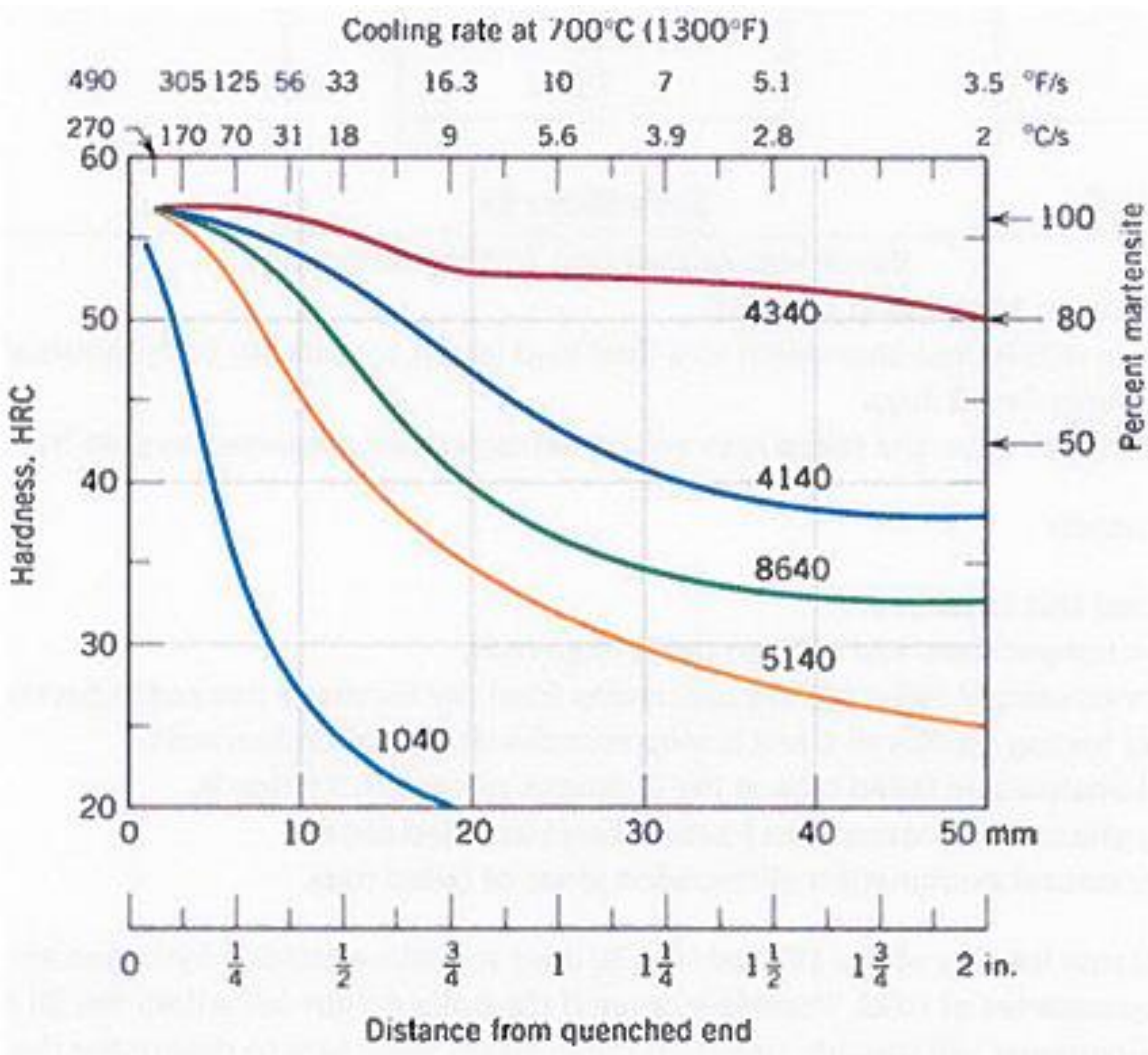


Figure 19 Hardenability curves for different low alloy steels and a medium carbon steel.

(a) 1 – Shear key, base plate anchor rods
3 – Shear key, top rods

(b) 2 – Bearing base, plate anchor rods
4 – Bearing, top rods

(c) 11 – Outrigger boom anchor rod at tower top[107]

Figure 20 Item numbers 2, 3, 4, and 11 for locations of rods for replacement with rods to be purchased with new supplementary requirements.[108]

[107] "The outrigger boom anchor rods act as pins for swinging out and then securing the maintenance outrigger boom at the top of 2 of 4 tower head chimneys. At each boom, one bolt is loaded and the other bolt is unloaded in the current boom position. The currently unloaded bolt will be installed snug tight when the boom is swung out for use (future position)."

[108] Reference 9, p.7

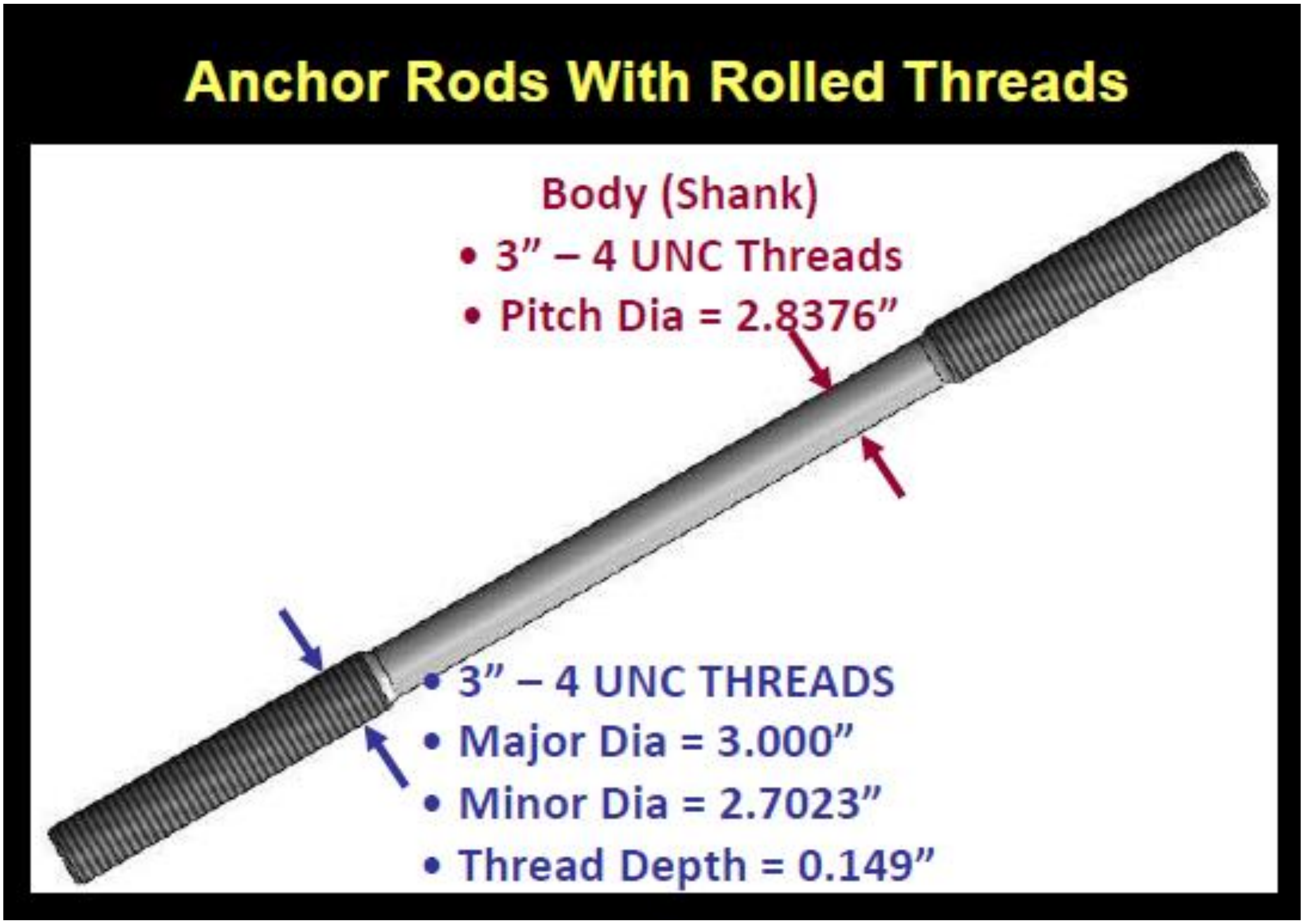
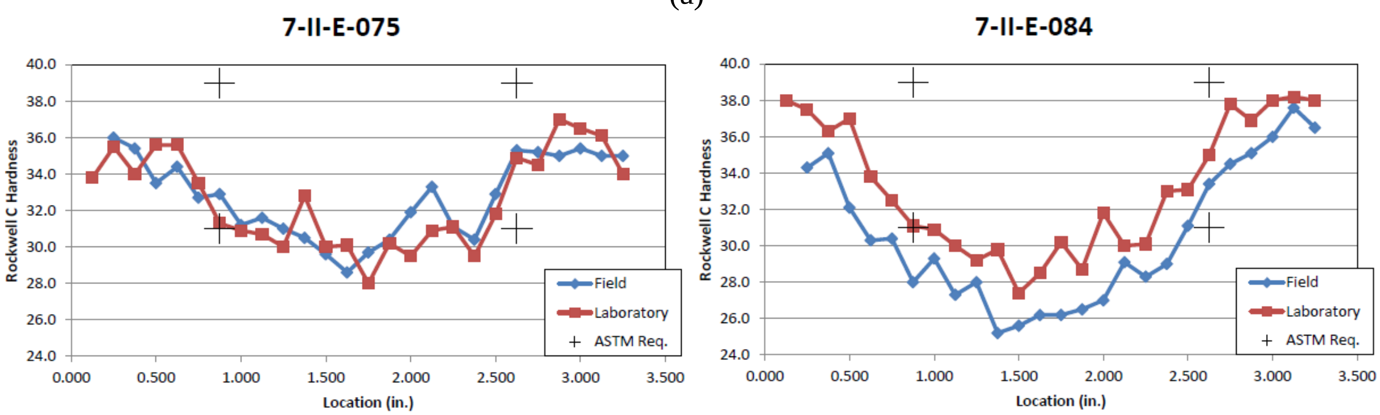


Figure 21 A 3 inch diameter rods with cold rolled 4UNC threads. The shank diameter is smaller than the thread major diameter.

ITEM 7. 3.5" PWS ANCHOR RODS - TEST II

Location (in)	7-II-E-075		7-II-E-084		7-II-E-090		7-II-E-092	
	OYN	Rolled	OOF	Cut	OQX	Rolled	OYI	Rolled
	Field	Laboratory	Field	Laboratory	Field	Laboratory	Field	Laboratory
0.125	-	33.8	-	38.0	-	35.8	-	31.1
0.250	36.0	35.5	34.3	37.5	37.0	37.8	33.2	34.2
0.375	35.4	34.0	35.1	36.3	39.0	38.4	30.9	34.8
0.500	33.5	35.6	32.1	37.0	38.3	38.0	31.1	34.8
0.625	34.4	35.6	30.3	33.8	36.4	33.5	32.9	33.5
0.750	32.7	33.5	30.4	32.5	35.6	34.2	33.5	33.8
0.875	32.9	31.3	28.0	31.1	34.1	30.1	31.2	31.1
1.000	31.2	30.9	29.3	30.9	30.3	30.0	30.8	30.8
1.125	31.6	30.7	27.3	30.0	30.7	30.5	30.8	29.7
1.250	31.0	30.0	28.0	29.2	27.1	29.0	31.4	26.1
1.375	30.5	32.8	25.2	29.8	31.2	29.3	28.0	26.8
1.500	29.6	30.0	25.6	27.4	31.1	29.0	31.0	28.1
1.625	28.6	30.1	26.2	28.5	32.2	29.5	29.6	33.5
1.750	29.7	28.0	26.2	30.2	31.6	28.7	29.6	27.0
1.875	30.4	30.2	26.5	28.7	30.4	30.0	28.8	28.3
2.000	31.9	29.5	27.0	31.8	31.6	29.0	30.1	31.4
2.125	33.3	30.9	29.1	30.0	29.7	30.8	32.4	31.1
2.250	31.1	31.1	28.3	30.1	32.7	30.3	32.8	34.5
2.375	30.4	29.5	29.0	33.0	35.1	31.9	33.8	35.0
2.500	32.9	31.8	31.1	33.1	33.6	32.8	34.1	34.1
2.625	35.3	34.9	33.4	35.0	34.1	34.0	33.1	34.8
2.750	35.2	34.5	34.5	37.8	39.0	37.5	34.4	34.7
2.875	35.0	37.0	35.1	36.9	35.7	37.5	35.2	34.8
3.000	35.4	36.5	36.0	38.0	38.2	37.5	35.2	35.6
3.125	35.0	36.1	37.6	38.2	39.9	37.3	33.0	35.5
3.250	35.0	34.0	36.5	38.0	39.0	37.2	35.4	37.1

(a)

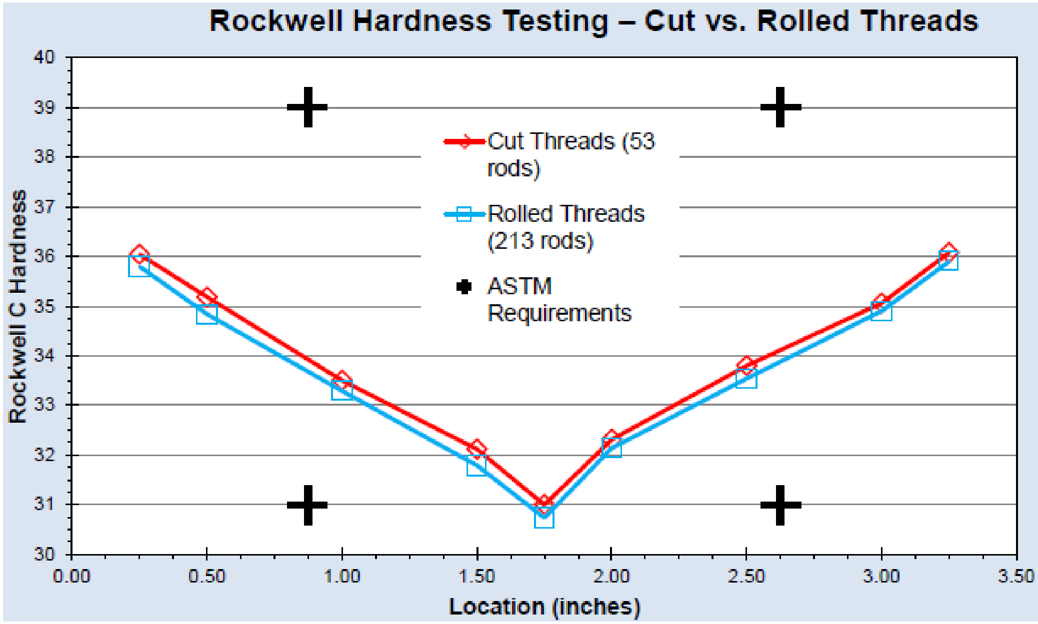


(b) Rolled Threads (c) Cut Threads

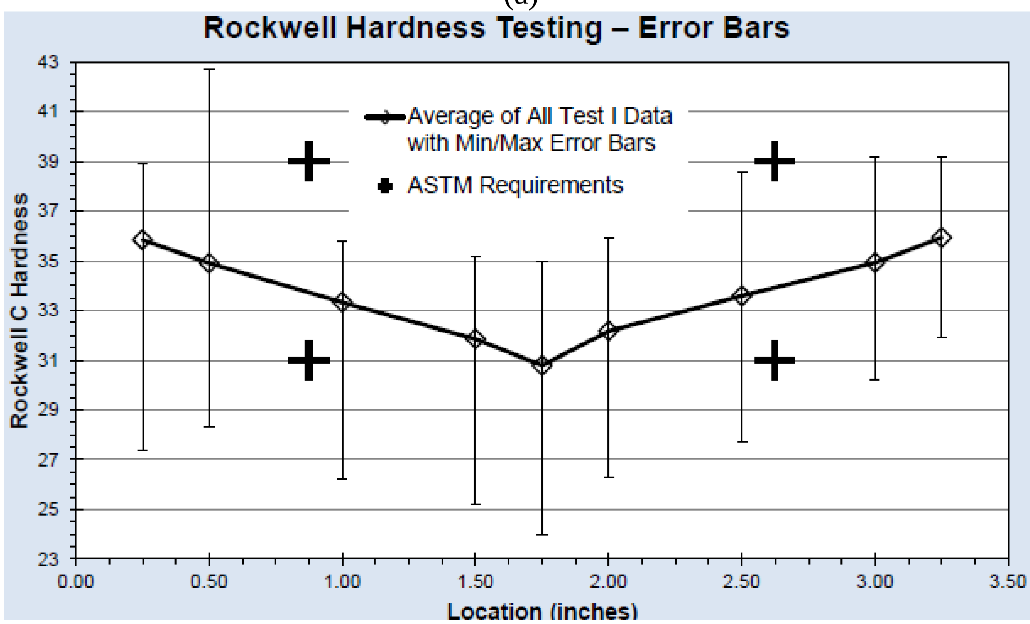
Figure 22 (a) Part of hardness data for 3½ inch PWS anchor rods. (b) and (c) Hardness traverse plots for Rod E-075 and E-084 in the table in (a).

PWS Anchor Rod Summary

Item 7 – 3.5" Diameter



(a)



(b)

Figure 23 Hardness traverse data for Item #7, 3½ inch PWS anchor rods, from File E17.

The title of (b), "Error Bars," is mislabeled for "Range Bars." The spread in the hardness data should not be labeled as a testing error.

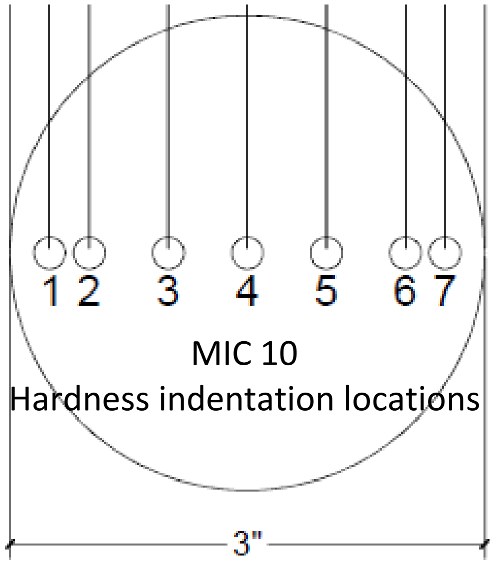
Table 13 Summary Results of Testing for Susceptibility to SCC

Item #		Microstructure	Surface Hardness of Tested Rods (HRC)	Mode of Fracture	Toughness CVN at 40° F (ft-lb)
#1	Shear Key Anchor Rods (2008)	Incomplete martensitic transformation with alternate layers of ferrite and pearlite, and inclusions.	37.6 (avg) 36.9 – 38.2 (min – max) (Metallurgical Report)	Brittle	13.5 (avg) 13 - 14 (min - max)
#2	Bearing & Shear Key Anchor Rods	Essentially Martensitic Structure	34.8 (avg) 29 – 39.3 (min – max)	Ductile	37.3 (avg) 35.5 – 39.5 (min - max)
#3	Shear Key Rods (top)	Essentially Martensitic Structure	35.1 (avg) 29.4 – 38.8 (min – max)	Ductile	36.9 (avg) 35 – 39 (min - max)
#4	Bearing Rods (top)	Essentially Martensitic Structure	36.7 (avg) 33.7 – 38.6 (min – max)	Ductile	26.7 (avg) 22 – 31 (min - max)
#5	Bearing Assembly	Not tested	36 (avg) 33 – 37 (min – max) (QC/QA Data)	Ductile (QC/QA Data)	Not tested
#6	Bearing Retainer Ring Plate Assembly	Not tested	35 (avg) 32 – 37 (min – max) (QC/QA Data)	Ductile (QC/QA Data)	Not tested
#7	Parallel Wire Strands (PWS) Anchor Rods	Essentially Martensitic Structure	35.9 (avg) 25.1 – 38.9 (min – max)	Ductile	39 (avg) 28 – 52 (min - max)
#15	East Saddle Tie Rods	Not tested	35.8 (avg) 32.5 – 37.5 (min – max)	Ductile (QC/QA Data)	17.8 (avg) 17 – 18.5 (min - max)

Figure 24 Partial display of Table 13 of the TBPOC report, showing a summary of Tests I (in-situ field hardness test), II (lab test), and III (full size test). The title of this table in the TBPOC report was mislabeled in two places. Table 13 is mislabeled. It presents no data from the stress corrosion test (or the Townsend Test).

Only the item #1 (Shear Key S1 and S2 anchor rods or the 2008 rods) is listed as having "incomplete martensite transformation" and "brittle" whereas the rest as having "essentially martensitic structure" and "ductile," a result of erroneous interpretation of data.

Shear Keys



S1A1		S1D2		S1D10	
1	32.9	1	32.9	1	32.7
2	34.0	2	34.0	2	31.5
3	31.8	3	31.8	3	32.5
4	33.3	4	33.3	4	31.9
5	32.2	5	32.2	5	32.9
6	35.1	6	35.1	6	33.1
7	34.1	7	34.1	7	32.7

S2J3		S2K3		S2B10	
1	34.2	1	32.1	1	33.2
2	34.9	2	26.2	2	36.3
3	33.9	3	30.0	3	32.6
4	37.7	4	31.2	4	33.8
5	33.8	5	30.2	5	35.7
6	35.2	6	33.4	6	33.8
7	35.7	7	31.5	7	36.8

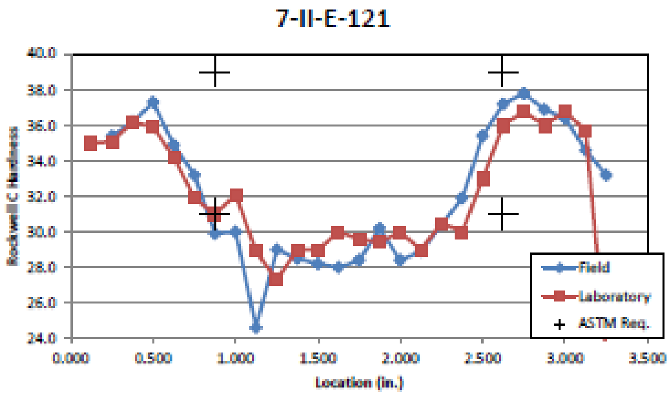
S3K4		S3A7		S3B7		S3J7		S3H9		S3A10	
1	31.2	1	31.3	1	33.0	1	33.4	1	30.4	1	34.7
2	31.8	2	35.6	2	32.4	2	33.7	2	34.2	2	36.7
3	30.5	3	32.2	3	33.9	3	36.6	3	33.6	3	33.5
4	33.1	4	34.5	4	35.2	4	36.2	4	35.1	4	37.5
5	31.0	5	28.7	5	34.4	5	37.2	5	34.3	5	35.7
6	33.7	6	26.2	6	34.8	6	38.7	6	28.9	6	31.6
7	31.3	7	32.9	7	34.7	7	35.1	7	31.0	7	34.9

Tower Base

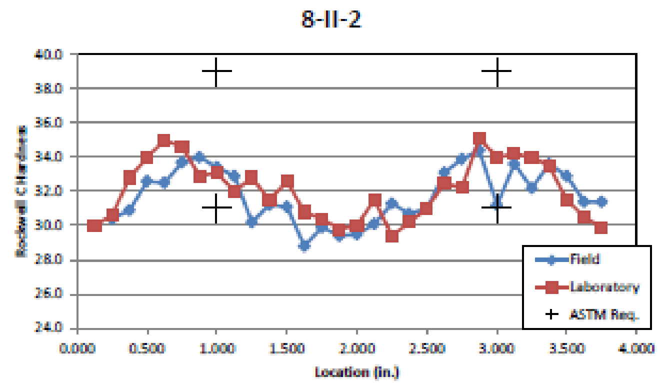
Anchor Rod	Diameter	Hardness Readings for 3" Ø Rods						
		1	2	3	4	5	6	7
E01	3"	36.0	35.2	34.6	33.3	33.9	34.6	35.4
E02	3"	36.2	35.5	33.4	32.2	33.8	34.9	36.3
E03	3"	35.0	33.6	34.0	32.0	32.1	33.6	35.7
E66	3"	36.1	35.4	34.0	33.9	33.7	34.6	36.2
W41	3"	36.1	35.3	33.8	33.7	34.6	35.6	35.5
cE-23	3"	35.8	35.6	35.0	34.9	35.1	36.1	37.0

Figure 25 Sketch showing the locations of potable hardness test indentations and examples of hardness traverse data that would look flat if plotted.[109]

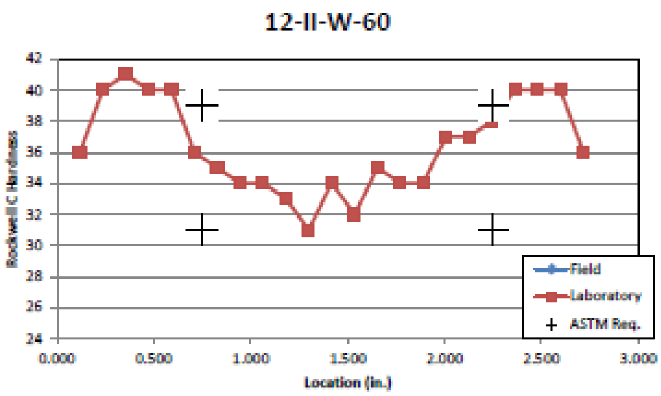
[109] File E17 SAS A354 BD Testing Program Results, Test I, II & III, http://www.mtc.ca.gov/projects/bay_bridge/A354/Appendix_E_Rod_Project_Binders/E17.pdf



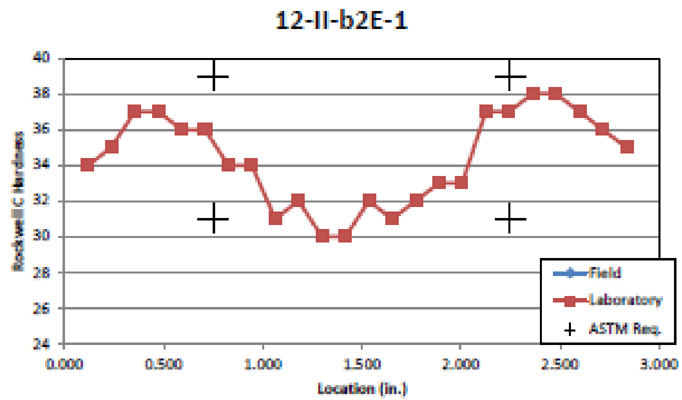
(a) Item 7, 3.5” PWS Anchor Rod – Test II



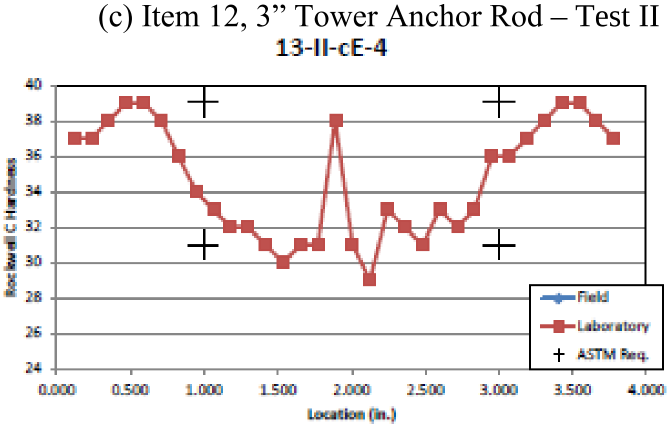
(b) Item 8, 4” Tower Saddle Tie Rod – Test II



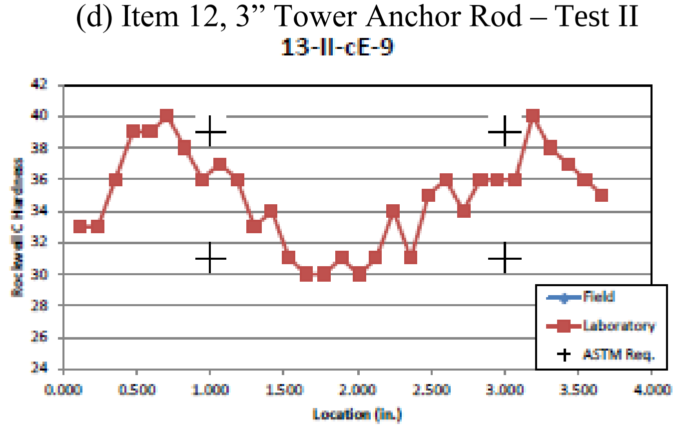
(c) Item 12, 3” Tower Anchor Rod – Test II



(d) Item 12, 3” Tower Anchor Rod – Test II



(e) Item 13, 4” Tower Anchor Rod – Test II



(f) Item 13, 4” Tower Anchor Rod – Test II

Figure 26 Examples of hardness traverse curves that are M shaped. The hardness for surface layer is lower than that at ½ inch from the surface. This is an anomaly for 4140 steel rounds that were quenched and tempered properly.

Caltrans needs to conduct a metallurgical evaluation to determine the reasons why the hardness traverse are M-shaped, rather than bowl shaped, and the effects of M-shaped hardness distribution on environmental hydrogen embrittlement (EHE) or long term stress corrosion cracking as defined by the TBPOC.