SAS PIER E2 HOT DIP GALVANIZED GRADE BD ANCHOR ROD FAILURES

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TABLE OF CONENTS

1.0 INTRODUCTION

During the 1989 Loma Prieta earthquake, one end of a section of the upper deck of the eastern span of the San Francisco-Oakland Bay Bridge dropped to the lower deck (Figure 1a). A new earthquake resistant bridge to replace the estern span is now in the final stage of construction. In March 2013, 32 of the 96 high strength steel anchor rods for two shear keys (S1 and S1) in Pier E2 of the new self-anchored suspension (SAS) bridge failed within days after they were tensioned. Since then, Caltrans[1] has been unable to articulate why these huge high strength steel anchor rods (3-inches in diameter x up to 24-ft in length) failed.

On April 10, 2013, Caltrans presented "the effort to diagnose and repair steel rods" and findings to the Commissions of the Bay Area Toll Authority (BATA).[2] Caltrans was still saying: "Engineers are continuing to disgnose the cause [of the anchor rod failures]" and "We don't know enough to say ..." These anchor rod failures are a classic case of bad materials engineering that allowed the Pier E2 high strength steel anchor rods to fail due to hydrogen embrittlement (HE). No other failure mechanisms than HE can account for these failures. In fact, the fractorgraphs that Caltrans presented at the April 10 meeting (and reproduced here as Figure 7) were a textbook case of HE failures of high strength steels.

The confusion surrounding these anchor rod failures reflects the lack of expertise by Caltrans in materials engineering and, specifically, in the nature of HE failures of high strength steels. Caltrans specification requirements on the Pier E2 anchor rods were inadequate and allowed these failures to occur. What is more troubling is that Caltrans has been oblivious to the possibility of these anchor rod failures due to HE during the 150 year design life of the new bridge. The metallurgical conditions of these anchor rods clearly pose such a risk. When the full potential of these HE failures during service with the 256 not-yet-broken anchor rods in Pier E2 is known, it could deal a serious blow to the trust of the earthquke worthiness of the new bridge and any remedial designs or solutions to counter act the failed and yet-to-fail anchor rods.

The April 10 meeting showed that Caltrans, MTC,[3] BATA Oversight Committee, and TBPOC[4] all could benefit from an independent evaluation that can clarify that the Pier E2 anchor rods failed because of hydrogen embrittlement (HE). It would be important for Caltrans to realize that some of them can still fail during service in the years to come due to the same HE mechanism. Any remedial schemes or the plan to open the new Bay Bridge on the 2013 Labor Day must have accounted for this possibility of future HE failures of the anchor rods during service (before an earthquake). Caltrans must know which of the 256 remaining anchor rods could fail due to HE during service and must replace them before design changes can be made, accepted, or implemented.

As recently as April 17, 2013, an MTC employee said to a TV reporter, "We know that there was an excess of hydrogen. We're looking into at what point in fabrication process this became a problem."[5] The hydrogen entry into the steel during anchor rod manufacturing is a secdondary issue because hydrogen can enter the anchor rod steel from the environment during service. Caltrans still does not understand that the Pier E2 anchor rods failed because, first of all, the anchor rod steel itself was susceptible to HE. Their susceptibility to HE was high because they were too strong or too hard at the surface. And, the blame goes

[1] Caltrans: California Department of Transportation
[2] http://www.mtc.ca.gov/news/current_topics/4-13/sfobb.htm
[3] MTC: Metropolitan Traffic Commission
[4] TBPOC: Toll Bridge Program Oversight Committee
[5] http://abclocal.go.com/kgo/story?section=resources/traffic&id=9069067

to Caltrans' specification as to why these conditions exist in the Pier E2 anchor rods. The reasons for this is explained in 2.5 (Hardness Requirements and Hardness Test Locations).

The zinc coating on the Pier E2 anchor rods would increase their susceptibility to HE failures. Caltrans should have established a maximum surface hardness requirement that would have made the Pier E2 anchor rod steel more HE resistant than anchor rods without zinc coating. Caltrans took no such precautions. They were concerned only about the hydrogen entry into the steel during anchor rod manufacturing. This simplistic approach to HE failure prevention by Caltrans was obviously inadequate.

A BATA employee also said to the TV reporter, "The focus at this time is to come up with the best solution that will give the seismic performance that's required. Then, we worry about culpability later."[5] A "solution" would have to be dependent upon how many of the remaining 256 anchor rods are likely to fail due to HE or to form HE cracks (but not yet completely broken) before an earthquake hits. A "best solution" would remain questionable until Caltrans know how bad the remaining 256 anchor rods are in terms of their possibility of HE cracking during service.

The possibility of future inservice HE failures of the Pier E2 anchor rods was not even acknowledged at the April 10 meeting. Caltrans and the Commission need to understand that the most important factor in high strength steel anchor rod failures due to HE is whether or not the steel itself was susceptible to HE cracking. If any of them is susceptible to HE by being too hard, it could fail some time during service, in months to years.

The material test reports submitted by the anchor rod supplier (Dyson) as well as the tensile test results produced by Caltrans' Transportation Testing Laboratory showed that HE failures of the Pier E2 anchor rods during service would be possible as will be discussed later. Caltrans has, however, no data that could correlate to the possibility of inservice HE failures of individual anchor rods in Pier E2. This is why Caltrans must conduct insitu surface hardness testing of all the anchor rods in Pier E2, including those that failed, before anything else. This will be a quick test. The results will be very valuable for Caltrans. This was not included in the testing protocols that Caltrans presented at the April 10 meeting. The surface hardness data may be correlated to the susceptiblity of individual anchor rods. The ones with hardness being too high are potential inservice HE failures and should be replaced.

If Caltrans had established a conservative maximum hardness for the surface of the Pier E2 anchor rods, no anchor rod failures would have occurred. Instead, Caltrans has been concerned only about hydrogen entry into the steel during anchor rod manufacturing. The shear key anchor rods failed in March 2013 more because of the hydrogen that entered the steel while they were sitting in the anchor rod holes for some five years than because of the hydrogen that was already present in the steel when Dyson manufactured the anchor rods. This is one of the main reasons why all of them failed in the bottom end.

Caltrans also needs to establish a new surface hardness test requirement for replacement anchor rods. The requirements of the existing specification were inadequate and allowed the anchor rods that were suceptible to HE, leading to the Pier E2 anchor rod failures.

Most background data including supplier's material test reports in this report came from the files released by Caltrans, following the April 10 BATA meeting.[6]

[6] http://www.dot.ca.gov/hq/paffairs/AnchorRods/

2.0 ANALYSIS OF CALTRANS' DATA AND DISCUSSIONS

2.1 Description of Anchor Rod Failures in Pier E2 of the New Bay Bridge

The new eastern span of the Bay Bridge has the world's largest self-anchored suspension (SAS) bridge. It is supported by three piers, Pier T1 (tower), Pier E2, and Pier W2 (Figure 1c).

Pier E2 has a reinforced steel concrete cap beam, where 4 shear keys (S1 – S4) and 4 bearings (B1 – B4) were installed. They "are designed to restrain the bridge decks during a large seismic event."[2] Figures 2a and 2b are top and elevation drawings and a bird-eye view of the Pier E2 cap beam, showing the high strength steel anchor rods to hold down S1 – S4 and B1 – B4.

These anchor rods are 3-inches in diameter x 9 to 24-ft in length. Caltrans specified that the these anchor rods be made to the requirements of ASTM A354, Grade BD,[7] dry grit blast cleaned to near white, and hot dip galvanized within four hours of blast cleaning.[8] Caltrans imposed no other additional requirements such as a 100% hardness check on the surface of the anchor rods for a maximum hardness to avoid high strength steel anchor rod failures due to hydrogen embrittlement (HE).

Each of the four shear keys (S1 – S4) has 48 anchor rods through a shear key stub base plate steel casting.[9] Each of the four bearing (B1 – B4) has 24 anchor rods. A total of 288 anchor rods are used to hold 4 shear keys and 4 bearings between the Pier E2 cap beam and the East and West Decks. Figures 3a and 3b show B1, S1, and B3 on the Pier E2 cap beam. Photographs of a bearing and a shear key are shown in Figure 4.

The anchor rods for two shear keys, 48 each for S1 and S2, were purchased in 2008 and installed in the Pier E2 cap beam. They sat in oversized anchor rod holes for five years. They were tensioned on March 1 – 5, 2013, using hydraulic tensioners to 0.75Fu (75% of the specified minimum ultimate tensile strength, 140-ksi, or 629.6-kips) to achieve a target pretension stress of 0.7Fu.[10] Caltrans found the first broken anchor rod on March 8, followed by 31 more or 33% of the 96 anchor rod failures by March 15. For S1, 21 of the 48 anchor rods or 44% failed. For one side of S1, 9 of 16 anchor rods or 56% failed. For S2, 11 of the 48 anchor rods or 23% failed. The unfailed rods were detensioned to 0.45Fu to prevent them from failing. Some time during early April 2013, the 256 unbroken anchor rods were tentioned.

All failures of the shear key anchor rods occurred at the bottom ends, which were held by anchor plates and nuts, embedded in concrete and grout (Figure 5a).[11] The top ends of the failed anchor rods would pop out as shown in Figure 6a since they remained under static tension ever since they were tensioned (or preloaded).

Only the hydrogen embrittlement (HE) cracking mechanism could be responsible for these anchor rod failures. This is a well-documented and well-publicized failure mechanism. No metallurgical failure analyses are even necessary to arrive at this conclusion. In adddition, the fractographs presented at the

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[7] ASTM A354 Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners.

[8] State of California, Department of Transportation (Caltrans), NOTICE TO CONTRACTORS AND SPECIAL PROVISIONS, Contract No. 04120F4, August 1, 2005.

[9] 2770 x 2770 x 275-mm ~ 109 x 109 x 10.8-inches.

[10] F_{actual} = 629.6/Seating Loss Factor = 629.6/1.10 = 569.9-kips, equivalent to σ = 95.5-ksi static tension <115-ksi SMYS (specified minimum yield strength for A354 Grade BD).

[11] Anchor plate: 80 x 250 x 300 (3.2 x 9.8 x 11.8-inches)

April 10 BATA meeting,[12] reproduced in Figures 6b and 7, are unequivocal evidence that the anchor rods failed due to the HE mechanism. It is prone to occur in high strength steel fasteners including Grade BD anchor rods as will be discussed later.

These failures coould have been avoided if Caltrans had specified a maximum surface hardness such as 36-HRC[13] or a lower maximum and a 100% surface hardness check even at an expense of lowering the minimum specified tensile strength, for example from 140-ksi minimum for ASTM A354 Grade BD to 125-ksi minimum.

2.2 Hydrogen Embrittlement as the Cause of the Pier E2 Anchor Rod Failures

Metal failures may be broadly divided into three categories, as follows.

(1) Overload cracking, typically during a rising load, as in during over-tensioning of anchor rods
(2) Fatigue cracking due to fluctuating or cyclic loadings (not applicable to anchor rods)
(3) Stress corrosion cracking (SCC) or hydrogen embrittlement (HE) under sustained static tensile stresses, applied, residual, or both

The Pier E2 anchor rods for S1 and S2 failed not during tensioning but while they were under a static load below the yield strength for several days. They were just "sitting tight," experiencing no additional applied loading such as cyclic or rising loads. Of the three categories listed above, only the last one is applicable to the anchor rod failures. So, the Pier E2 anchor rod failures had to be due to the third category, due to SCC or HE.[14]

As the name HE (hydrogen embrittlement) suggests, hydrogen was obviously one of the key factors. Hydrogen could have been present in the anchor rod steel in more than a minimum amount necessary to cause HE before the anchor rods were installed or could have entered the steel while sitting in the anchor rod holes for some five years.

HE failures due to the hydrogen already present in new high strength steel products has been referred to as internal hydrogen embrittlement (IHE). The HE failures due to the hydrogen that diffused into the steel from environment while in service are referred to as environmental hydrogen cracking (EHE).[15] The anchor rods for S1 and S2 could have failed due to EHE rather than due to IHE. Raymond stated, "No IHE failures do not mean no EHE failures."[16] As a source of hydrogen for EHE, he also stated, "During service under stress in a moist environment [such as in the San Francisco Bay], due to galvanic couple between [zinc] coating and steel acting as an insitu hydrogen generation pump."[16] This is why the Caltran's approach to avoid HE in the Pier E2 anchor rods by controlling the hydrogen entry into the steel only during anchor rod manufacturing was ill conceived from the beginning.

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[12] http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2032/5_BATA_Oversight_April_10_2013_additional.pdf

[13] HRC: hardness number on the Rockwell C scale. This number, 36-HRC, is only an example. Caltrans or "the Engineer" is responsible for setting its own maximum hardness requirement to avoid hydrogen embrittlement in hot dip galvanized high strength steel anchor rods.

[14] There are fine distinctions between SCC and HE. In the case of the high strength steel failures in [moist] air under static loading, it is generally agreed that the failure mechanism is HE rather than SCC. One distinctive difference between the two is that cathodic protection (CP) suppresses SCC but accelerates HE.

[15] In some literature, EHE is also referred to as stress corrosion cracking (SCC) because the hydrogen is generated as a byproduct of corrosion of, in this case, zinc which is anodic to steel.

[16] http://www.asetsdefense.org/documents/Workshops/SustainableSurfaceEngineering2009/Agenda/Thursday/Raymond%20-%20For%20Posting.pdf L. Raymond & Associates

HE is a time dependent failure mechanism, like fatigue failures. Unlike overloading failures which occur almost instantaneously in seconds, fatigue, SCC, and HE failures involves a crack nucleation, growth, and a final fracture that occurs when the remaining cross section that was steadly weakening over time can no longer withstand the stress, applied, residual, or both. It is difficult to tell how long this crack growth stage might last. Sometimes, the first microscopic crack initiation would occurr after a long "incubation period." It would be possible, therefore, that some anchor rods may contain partially through cracks, waiting to fail completely when an earthquake hits.

The fracture face of one of the failed anchor rods, shown in Figure 6b, has a crescent shaped area at arrows A1-2-A3-A4. This area is relatively smooth as compared with the rest between arrows A4 and A5, marked FFZ (fast fracture zone). The crescent area, marked HEZ (hydrogen embrittlement zone), was formed by HE during the serval days after the rod was tensioned to 0.7Fu or to 95.5-ksi tensile stress.[10] Since this is below the specified minimum yield strength of 115-ksi for ASTM A354, Grade BD, the anchor rod should not have failed under a normal rising load or under a static sustained load without being influenced by HE.

In high strength steels which are susceptible to HE failures, microscopic cracks would form along points of stress concentration, typically at the root of the first thread engagement with a nut. These cracks would grow in size with time, steadly decreasing the load carrying capacity of the anchor rod. When the stress in the remaining cross section, marked FFZ (fast fracture zone), exceeded the tensile strength of the anchor rod, the HE crack that had grown in size to arrow A4 propagated rapidly to the other side at arrow A5, completely fracturing the anchor rod. The size of an FFZ would be determined by the stress level (σ) and the fracture toughness (K_{Ic}) of the steel. Thus, the time to failure would be dependent upon the hydrogen concentration and the stress level for a given material condition.

The pie-cut section at arrow A6 in Figure 6b is shown enlarged in Figure 7a. Arrows A6, A7, and A8 point to three of several ridges, called ratchet marks, along the thread root where microscopic cracks formed due to HE. These ratchet marks indicate that microscopic cracks initiated at multiple sites along the thread root and grew in size over time. Arrow A9 points to the demarcation line between the HEZ and the FFZ.

Figures 7b top and 7b bottom are scanninig electron fractographs, magnified about 1000 times, of the boxed areas in Figure 7a. The fractographic appearance of the FFZ, shown at arrow A10 (or Figure 7b top), is distinctively different from that of the HEZ, shown at arrow A11 (or Figure 7b bottom). The latter shows that the fracture face of the HEZ consisted of grain boundary facets and numerous microscopic cracks along the grain boundaries. This is known as an intergranular fracture and is one of fracture characteristics of HE failure in high strength steels.[17] The FFZ at arrow A10, in Figure 7b top, displayed cleavage facets with river patterns and some fine dimples, characteristics of a relatively brittle and fast fracture in high strength steels.

2.3 Three Conditions for Hydrogen Embrittlement Cracking in High Strength Steels

For a high strength steel anchor rod to fail due to HE, it must satisfy the following three conditions simultaenously. Figure 8 illustrates this requirement for HE by using tri-circles, each representing one of the threee necessary conditions for HE.

[17] Hydrogen embrittlement cracks in other conditions can be transgranular.

(i) Susceptile material

First of all, the material (the high strength steel in this case) must be susceptible or pre-disposed to HE. Fortunately, HE is not a concern for most steels.

For normal atmospheric applications, HE is a problem only for high strength steels.[18] The higher the strength, the more susceptible the steel is to HE.

HE is not a new phenomenon. In the 1950's, landing gears of aircrafts collapsed, while parked, due to HE. In the 1970's, large diameter closure studs (over 4-inches in diameter) for nuclear reactors in power plants failed due to HE. One common factor in these failures is that the steels were "too strong" or "too hard," which made them susceptible to HE. For reactor closure bolting, the US Nuclear Regulartory Commission states: "The measured yield strength of the stud bolting material should not exceed 150-ksi."[19, 20] Some of the material test reports for the Pier E2 anchor rods, including some test reports by Caltrans' Structural Materials Testing Laboratory, listed yied strength higher than 150-ksi.

The susceptibilitty of high strength steel to HE would relate to its microstructure. It is, however, difficult to use the microstructure as an index of material's susceptibility to HE because the microstructure is difficult to quantify and subject to a wide variations of interprertations.

Experience has shown, however, that the higher the strength or the hardness, the more susceptible a high strength steel is to HE.[21] Low alloy steels, like 4140, heat treated to hardness of 40-HRC or higher at the surface, would be likely to fail due to IHE or due to EHE in moist air. Zinc coating, either electroplating or hot dip galvanizing, would increase the susceptibility of steel to IHE, EHE, or both. ASTM A490,[22] a companion to ASTM A354, is another specification for high strength steel structural bolts. The latest edition of A490 does not permit hot dip galvanizing on A490 bolts, probably because hot dip galvanizing would increase the material's susceptibility to IHE, EHE, or both.

Conversely, fasteners with or without zinc coating are not likely to fail due to HE if the hardness was lower than 33-HRC.[23] At this hardness level, the steel would be not susceptible to HE. So, it would be unwise to have ASTM A354 Grade BD hot dip galvanized without specifying a maximum surface hardness to ensure the steel would be low in HE susceptibility. Caltrans did not do this for the Pier E2 anchor rods as will be discussed later. This may be the primary reason why Caltrans is having anchor rod failure problems now.

Surface hardness is a good indicator of susceptibility of high strength steel to HE and can be used as a quality control tool to mitigate HE failures due to IHE, EHE, or both. This will be elaborated more on later.

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[18] In the presence of hydrogen sulfide in the environment as in oil fields and oil refineries, hydrogen embrittlement can occur in many different grades of steel. Then, hardness is limited to 22-HRC maximum for low alloy and carbon steel.

[19] NUREG 1.65 Materials and Inspection for Reactor Vessel Closure Studs, revision 1, April 2010, US Nuclear Regulatory Commission http://pbadupws.nrc.gov/docs/ML0920/ML092050716.pdf

[20] ksi = kilo-pounds per square inch or 1,000 pounds per square inch.

[21] For steel, there is a linear relationship between strength and hardness. The higher the hardness, the higher the strength.

[22] ASTM A490 Standard Specification for Heat-Treated Structural Bolts, 150 ksi Minimum Tensile Strength.

[23] ASTM F2329 – Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners

(ii) Hydrogen

Hydrogen is the smallest atom that can diffuse through most anything and can be found almost anywhere including steels. Hydrogen will be present during steelmaking and will be present in fresh-made steels. It will also enter the steel even during machining, not necessarily only during acid cleaning or electro-plating. Hydrogen will be produced as a byproduct of corrosion of steel, zinc, or both and would enter the steel during service. Hydrogen will get into the steel as long as there is a driving force such as a hydrogen concentration gradient. It is virtually impossible to have steel products completely free from hydrogen. To say "hydrogen was found [in the failed anchor rods]" means little.

Since the minimum amount of hydgen that can cause the initial microcracks to form in high strength steel under a static tension would be dependent on the stress level and the material's susceptibility to HE, it would be difficult to define the maximum hydrogen concentration that may be allowed for a high strength steel anchor rod as a means of avoiding HE failures. According to the literature, however, hydrogen concentrations as low as 1-ppm[24] or 3 to 4-ppm could cause HE cracking in high strength steels under high sustained tensile stresses.

It is not easy to determine the hydrogen concentration of a steel, particularly of the one that failed or near the fracture face of an HEZ. This is because the hydrogen is so mobile that it could easily diffuse out of the steel from the "crime scene" after the failure. As demonstrated by the Pier E2 anchor rod failures, hydrogen could have entered the steel while the anchor rods were sitting in the anchor rod holes for some five years before they were tensioned to 0.7Fu in early March 2013. Therefore, although precautions should be required to minimize hydrogen entry into the steel during anchor rod manufacturing, such as requiring dry grit blast cleaning instead of acid cleaning, hydrogen alone would be not a reliable factor to control for purposes of avoiding HE failures.

Whether the rainwater in the bottom of the Pier E2 anchor rod holes was even necessary for the S1 and S2 anchor failures is speculative.[25] Just the salt laden seawater mist, diurnal condensates, and fog in the air above the San Francisco Bay seawater could have increased the time of wetness of the anchor rod thread surfaces, in the crevices between the anchor plate/nut holes, and could have done the same corrosion damage as rainwater, if not worse. It seems unimportant, therefore, to try to pin down when or where the hydrogen entered the steel, causing the anchor rods to fail due to IHE or EHE. Caltrans is still continuing to trying to implicate Dyson by implying that the anchor rods already had high hydrogen concentation when Caltrans received them. This indicates that Caltrans has been concerned only about IHE and not with EHE.

(iii) Tensile stress

Tensile stresses are necessary in any fracture or cracking of structural members such as anchor rods. Intuitively, there must be a threshold stresss level below which HE cracking would not occur, just like a fatigue cracking threshold stress. It would be, however, difficult to define a threshold stress level for HE because it would be depdendent upon the other two factors discussed above:

[24] ppm: parts per million. A gallon of salt in an Olympic size pool water would be equivalent to 3-ppm (or 0.0003%) sodium chloride in water.

[25] 'Comedy of errors' led to bad bridge bolts, Published 11:01 pm, Thursday, April 11, 2013, http://www.sfgate.com/bayarea/article/Comedy-of-errors-led-to-bad-bridge-bolts-4428913.php

susceptibility of steel to HE and hydrogen concentrations. Generally speaking, however, the higher the tensile stress, residual, applied, or both, the shorter the time to failure.

Conversely, for a bolted connection to be effective, it must achieve a high clamping force. To do this, bolts or anchor rods are stressed to high stress levels, usually to 70 to 80% of the ultimate tensile strength (Fu) of the bolitng material. Thus, high sustained tensile stresses are unavoidable and may not be used as a means of mitigating HE in the Pier E2 anchor rods.

HE cracking is expected to occur when the three conditions in Figure 8 are simultaneously satisfied. HE may be mitigated by lowering any one of the three conditions. In reality, however, in bolted connections including anchor rod applications, the only practical option for mitigating HE is to lower the material's susceptibility to HE. This is done usually by requiring a maximum hardness at the surface of high strength steel. The maximum hardness requirements in ASTM A354 are problematic as will be discussed later. This must be augmented by "the Engineer" for specific applications such as Pier E2 anchor rods.

Caltrans did not do this. Instead, Caltrans forcused only on controlling the hydrogen entry into the steel during anchor rod manufacturing, specifically by requiring "dry blast cleaning" instead of the customary acid pickling in preparation of hot dip galvanizing. This was a good practice but insufficient by itself to avoid HE failures with the Pier E2 anchor rods as demonstrated by their failures in March 2013. Caltrans should have paid more attention to the susceptibility of the anchor rod steel as the primary factor in preventing HE failures. The other two factors, hydrogen concentration and stress, are not really applicable to avoiding HE failures in the Pier E2 anchor rod applications.

2.4 Effects of Stress Concentration on Anchor Rod Failure Locations

Figure 9a shows stress distributions in threaded members when they are engaged and stressed. The roots of the threads act like notches and will experience stress concentration effects.

In a bolted joint, the root of the first bolt thread that was engaged by the nut theads is where the highest stress would occur in the axial direction of the bolt (Figure 9b). This would be followed by the fillet between the underside of the head and the shank. This is why HE failures of bolts would occur at either one of these two locations. In the case of the Pier E2 anchor rods, each end engages a nut.[26] Therefore, the root of the first engaged threads at either end would be a candidate location for HE failures. In the anchor rods, the stress concentration effects at the roots of the first engaged threads would have been about the same between the top and the bottom ends. Of the 32 that failed, some had to fail at the top ends unless the bottom ends were subjected to some other additional factors.

The bottom ends were, however, exposed to more favorable conditions for higher hydrogen concentrations because they experienced longer time of wetness due to marine condensate or rainwater accumulation. Additionally, the zinc layer from hot dip galvanizing where the nut enaged in the bottom end would have higher probability of having been mechanically damaged,[27] with more discontinuities in the zinc layer than the top end.

[26] Misalignment or bending would be another factor that would influence the HE failure location.

[27] The hot dip galvanized zinc layer rarely contains micro-cracks as mentioned by a materials engineering professor in a recent article about the anchor rod failures. http://www.sacbee.com/2013/04/17/5350535/newly-released-test-results-show.html The cracks in the zinc layer he was referring to occur in galvanized steel sheet when plastically strained during forming. Anchor rods are subjected only to elastic strains and not to plastic strains. Therefore, the micro-cracks will not form in the zinc coating of anchor rods.

The above variables could explain why the S1 and S2 shear key anchor rod failures all occurred at the bottom ends. Thus, these failures at the bottom ends would be more attributable to EHE (due to the hydrogen from the environment) rather than IHE (due to the hydrogen that was already present in the anchor rod at Dyson). This observation alone should have stopped Caltrans from trying to implicate Dyson's quality control laspse for the anchor rod failures.

This interpretation is troubling, however, because it would suggest that all other ASTM A354 Grade BD anchor rods with hot dip galvanizing in Pier E2 could potentially fail during service due to EHE, provided the anchor rod steel is susceptible to HE by being too hard. It would be only a matter of time until some will fail. A one-month test in the Caltrans' testing protocol is far from adequate. When these failures might actually occur would be a matter of conjecture because Caltrans has no surface hardness data that can be used in judging the susceptibility of the Pier E2 anchor rod steel to EHE.

Caltrans' top priority now is to determine if any of the 256 (288 – 32 failed rods) anchor rods in Pier E2 could fail during service due to EHE. Caltrans needs to know this because it would impact any remedial designs to counter act the anchor rod failures, including the future inservice EHE failures, or the opening of the new bridge on the Labor Day. The only data that could give any clues as to how serious the possiblity of inservice EHE failures would be are surface hardness data. Caltrans has not been even concerned about surface hardness, let alone having collected such data and presented them to the Commision.

Caltrans should consider an insitu hardness check of all ASTM A354 Grade BD anchor rods in Pier E2 using a potable hardness tester such as Equotip 3. The test loction should be as close to the anchor rod surface as possible (but below a decarburization layer) and not deeper than the thread root. The ends of the exposed threads may be used for these hardness tests (as illustrated in Figure 14).

2.5 Hardness Requirements and Hardness Test Locations

High strength steel fasteners including anchor rods are prone to fail due to HE (both IHE and EHE) because they can easily satisfy the three conditions for HE, susceptible material, environment (hydrogen), and high stresses, simultaenously. The only practical way to avoid EHE failures of the Pier E2 anchor rods is to lower the susceptibility of the steel to HE and the only practical way to achieve this is to set a consertive maximum hardness limit for the anchor rod surface. Caltrans has neglected to do this,[8] allowed Dyson to produce the Pier E2 anchor rods that were susceptible to HE failures because of a surface hardness being too high, and caused the 32 anchor rod failures for S1 and S2 in March 2013. More failures could occur in the coming months or years if the current anchor rods remain in place. Caltrans needs to find out which one would be susceptible to EHE failures and which ones to replace.

Both ASTM A354 Grade BD and A490 require 38 – 39-HRC as a maximum hardness, as shown below.

	Tensile Strength, ksi	Yield Strength, ksi	Elongation %	Reduction of Area, %	Hardness			
					minimum		maximum	
					HB[28]	HRC	HB	HRC
ASTM A354 Gr. BD								
¼ - 2½ inches	150 min	130 min	14 min	50 min	311	33	363	39
>2½ - 4 inches	140 min	115 min	14 min	50 min	293	31	363	39
A490								
½ to 1½ inch, incl.	150 min 173 max	130 min	14 min	50 min	311	33	352	38

[28] HB: Brinell hardness number.

The minimum tensile strength requirements in ASTM A354 Gr BD for the ¼ - 2½ inch size group are the same as for ASTM A490, which is limited up to 1½ inch, inclusive. The purpose of these maximum hardness of 38 – 39-HRC, 173-ksi maximum tensile strength (which is equivalent to 38-HRC), or both, would be to avoid HE failures in ASTM A354 Grade BD and A490 high strength steel fasteners. If so, then, it would be difficult to understand why the Pier E2 anchor rods that met the requirements of ASTM A354 Grade BD have failed. The reason is simple: Caltrans neglected to establish a maximum hardness for the surface of the anchor rods, specific to the Pier E2 application. This lack of requirement for the anchor rod surface as the hardness test loction allowed Pier E2 anchor rods to be produced and supplied with high surface hardness, making them susceptible to HE failures. This is where "the Engineer" slipped. The path to this over-sight by Caltrans is as follows.

The ASTM A354 Grade BD anchor rods in Pier E2 all came from Dyson, 96 for S1 and S2 in 2008 and 192 for the rest in 2010. Dyson chose 4140 low alloy steel to manufacture all of the Pier E2 anchor rods. This is one of low alloy steels that is commonly used for high strength steel fasteners.

The hardenability of 4140 steel is, however, relatively low. As the diameter increases, the hardness (and strength) that can be attained by heat treatment would decrease because of slowed cooling rates during hardening heat treatment. This is why ASTM A354 Gr BD has two sets of tensile property requirements, one for ¼ - 2½ inches and another for >2½ - 4 inches. The requirements for the latter are lower than the former as shown above to account for the mass effects on the cooling rates during hardening heat treatment. The larger the diameter, the lower the cooling rates during oil quenching for hardening heat treatment, resulting in lower hardness and strength than a smaller size.

The hardness and strength across the diameter would be not uniform because the cooling rate at the surface of a round steel bar is higher than that at the core during oil quenching for hardening. The hardness and strength will be always higher at the surface than those at the interior or core. The hardness curve across the diameter of a 3-inch 4140 steel anchor rod would look like that in Figure 10a when it was heat treated by oil quenching from 1600°F and tempering at 1025°F as was done by TC Industries and Gerdau MacSteel for Dyson.[29,30]

Referring to Figure 10a, a 3-inch diameter 4140 steel anchor rod can have 38-HRC at mid-radius (or r/2), and 41-HRC at the surface. The latter would exceed the maximum hardness of 39-HRC for ASTM A354 Gr BD and should not be acceptable. This would be still acceptable, however, under the test methods of ASTM F606,[31] to which ASTM A354 refers for testing, and also according to ASTM A370.[32] Caltrans should have recognized this problem in ASTM specifications and should have made the anchor rod surface as the hardness test location specifically for the Pier E2 anchor rods and required a 100% hardness check at both ends of each anchor rod.

The most important factor that allowed Dyson to supply the Pier E2 anchor rods that were susceptible to HE is the lack of additional surface hardness requirements with a 100% surface hardness check by Caltrans. It would be no surprise to learn if the failed anchor rods had a surface hardness of 40-HRC or

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[29] For example, TC Industries Test Report No. 141224, HT M644914, A4140 3"RD x 17'2", Surface HB 363, August 18, 2008.

[30] For example, Gerdau MacSteel, Heat No M32854, WO 228544 101, Date: 7/13/09

[31] ASTM F606 Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indictors, and Rivets.

[32] ASTM A370 Standard Test Methods and Definitions for Mechanical Testing of Steel Products

higher and thus were susceptible to HE. Caltrans presented no hardness data at the April 10 BATA meeting.[2]

In the absence of any specific additional test requirements, Caltrans as the buyer must accept the ASTM A354 Gr BD anchor rods with surface hardness of 41-HRC against the 39-HRC maximum for ASTM A354 Gr BD so long as the hardness at r/2 was lower than 39-HRC. The reasons are as follows.

For routine hardness tests [of finished products], ASTM F606 states, "tests shall be conducted on the unthreaded shank, end of the bolt or stud or at the arbitration location."[33] These different hardness test locations would produce different hardness numbers because steel bolts and anchor rods are seldom uniform in hardness or strength across the diameter, particularly for large diameters, as discussed above. ASTM F606 states further, however, "For purposes of arbitration between the purchaser and the seller over reported tests, hardness tests shall be conducted at the mid-radius (r/2) of a transverse section …" as illustrated in Figure 10b.[34] Thus, a 3-inch ASTM A354 Gr BD anchor rod with 38-HRC at r/2 (mid-radius) and 41-HRC at the surface would have to be acceptable to the buyer (Caltrans) based on the 38-HRC at r/2, completely ignoring the higher hardness, 41-HRC, at the surface. Caltrans should have recognized this problem and should have specified a maximum hardness at the surface of the 3-inch diameter anchor rods.

The surface hardness of 41-HRC would, however, pose a serious risk because the metal with the surface of 41-HRC would be far more susceptible to HE than the one with 38-HRC. This is probably the most important factor in the Pier E2 anchor rod falures in March 2013. Their surface hardness had to have been 39-HRC or higher. Caltrans has no data to disprove this scenario because Caltrans has not recognized the importance of the hardness at the surface of the anchor rods and has not done surface hardness tests.

In addition to making the anchor rod surface as the hardness test location, Caltrans should have estasblished a maximum surface hardness which should have been lower than the 39-HRC maximum of ASTM A354 Gr BD. This is because the zinc coating that Caltrans required on the anchor rods would have increased the susceptibility of the anchor rods to HE failures as discussed before.

Some of the material test reports submitted by Dyson[35] as well as those obtained by the Structural Materials Testing Laboratory of State of California[36] reported 37 – 38 HRC with test location listed as "core" or "surface". Some listed no test location. TC Industries Test Center who heat treated 3" RD 4140 steel for Dyson reported 363-HB (equivalent to 39-HRC) as surface hardness.[37] TTML reported 35 – 38-HRC as core hardness.[38] In a telephpone conversation, however, TTML Lab Manager said that the hardness readings were taken at mid-radius. Gerdau MacSteel who supplied 269 bars of heat treated 4140 steel to Dyson reported 37-HRC as surface hardness for 10 of 269 bars.[39] Gerdau declined to discuss the hardness test locations over the telephone. Overall, however, Gerdau's 269 bars in 2009 had hardness numbers lower than the 95 bars heat treated by TT Industries for S1 and S2 in 2008. These hardness data would indicate, however, that some of the Pier E2 anchor rod steel had to have been high in surface hardness and are susceptible to EHE.

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[33] ASTM F606, 3.1.1.2

[34] ASTM F606, 3.1.3 and Figure 1 Hardness Arbitration Location.

[35] Tensile Testing Metallurgical Laboratory, Certified Test Report, 4140, HT M644912, No. A8-232-737, Date: 8-20-08. Reported 38-HRC core.

[36] SM Number 08-1088, A354 BD HDG, Date Tested: 08-21-08, Reported 36.97-HRC, No test location given.

[37] For example, TC Industries Test Center: Heat M644914, Date Aug 18, 2008.

[38] TTML: Tensile Testing Metallurgical Laboratory, Job No. A8-232-737, Date: 8-20-08.

[39] Gerdau MacSteel, Heat No M32854, WO 228544 101, Date: 7/13/09

Caltrans needs to make a complete inventory of surface hardness of all the anchor rods in Pier E2. The surface hardness data will prove useful in judging how serious the possibilities of EHE failures might be for the Pier E2 anchor rods.

2.6 Tensile Strength as a Measure of HE Susceptibility

The tensile strength of steel is linearly proportional to hardness. Tensile strength can be used as a guide to judge the susceptibility of bolting material to HE. This approach is, however, less expedient than hardness as a guide because a tensile specimen cannot represent the properties at or near the surface.

For tensile tests of ASTM A354 Grade BD anchor rods, Dyson chose the option of using machinied tensile specimens rather than doing full size pull tests.[40] Figure 10c is a sketch that illustrates the location of a machined tensile test specimen from a large diameter bolt or anchor rod. The centerline of the tensile specimen is at r/2 of a bolt or anchor rod cross section. This is consistent with the "arbitration hardness test location" at r/2 as stipulated in ASTM F606.

Several of the tensile properties reported by Dyson as well as those tested by the Caltrans' Laboratory listed tensile strengths in excess of 170-ksi (equivalent to 38-HRC) and yield strengths in excess of 150-ksi. Considering that all of these properties were obtained from tensile specimens at r/2, the surface hardness would have to be around 40-HRC or higher. This would also support the concern that at least some of the Pier E2 anchor rods had to have a surface hardness of 40-HRC or higher and thus are susceptible to HE.

The test reports with a tensile strength higher than 170-ksi and a yield strength higher than 150-ksi should have raised a red flag as a potential HE danger for the anchor rods, requiring a further probe. These specimens that showed a high strength, of course, displayed low elongation values. For example, Caltrans' Laboratory reported the following results.

Transportation Laboratory, Report of Tests, SM No: 08-115, Date: 9-8-08						
Sample No	Heat No	Ultimate, psi	Yield, psi	Elongation, %	RA, %	
26A	M644914	160,730	151,606	12.5	Not reported	
26B	M644914	165,980	147,456	14.4	Not reported	
30A	M644914	170,080	153,241	13.6	Not reported	
30B	M644914	173,350	157,985	13.3	Not reported	
Min req't Gr BD		140,000	115,000	14	50	

In another report by the Caltrans' Laboratory, the above elongation values less than the 14% minimum were accepted by noting "OK per RA." Actually, the elongation values should have been reported using two significant figures. So, 13.6% should be reported as 14% and 13.3% as 13%. These elongation values, 1 or 2% lower than the 14% minimum required, have no engineering significance. Elongation is only a rough indicator of steel's ductility. Elongation values are not used in any design calculations of any structural members.

Figures 11a – 11d show exemplar tensile specimens after testing. Ductil steel would stretch and neck down before breaking (Figures 11a, 11b, and 11c) whereas brittle steel would just break without stretching or necking down (Figue 11d). Figure 11e is the fracture face of a ductile steel pin. It broke in a

[40] Full size pull tests were performed by Caltrans' Structural Materials Testing Laboratory.

brittle manner when overloaded at high strain rates in a cold morning. A tensile test from the broken pin showed as much as 20% elongation. So, high elongation values in tensile tests do not guarantee a ductile behavior under stress.

The low elongation values obtained by Caltrans Testing Laboratory shown above were not an indication of high concentration of hydrogen in the steel. Although hydrogen in high concentrations would lower the ductility, the amount of hydrogen required for HE is usually so small and concentrated near the surface that the conventional tensile tests would not detect the effects of hydrogen on ductility (elongation). The above infractions in elongation would have no impact on the anchor rod performance except that the low elongation values are indicative of high strength or high hardness, which should have been a concern from the point of susceptibility to HE. In general, the higher the strength, the lower the ductility. Therefore, it would be imprecise to say that hydrogen in the anchor rod steel made the steel brittle. It would be more correct to say that hydrogen caused a brittle fracture due to HE because even ductile steel can break in a brittle manner under certain conditions.

2.7 Variability of Hardness of Anchor Rods

Dyson used the same grade of steel, 4140, same heat treatment, and same hot dip galvanizing procedues to produce all the anchor rods in Pier E2. Yet, some anchor rods were higher in hardness and strength than others. This variability is mainly due to the hardenability band allowed for each grade of steel, which is related to the ranges of alloying elements, i.e., chemical compositions.

Figure 11a is an example of hardenability band for a low alloy steel similar to 4140. At 20-mm (equivalent to r/2 of a 3-inch diameter rod) from the hardening end, the hardness can vary from 32-HRC to 47-HRC for this particular alloy. When tempered, this hardness range would narrow down but would persist. This is the major source of hardness variability from one anchor rod to another.

The next factor that would affect the hardness would be the cooling rate. One of the factors that would affect the cooling rate would include the metal temperature at the time of oil quenching. Some anchor rods are as long as 24-ft, which may experience temperature variance along the length in furnace. The hardness of one end of a long anchor rod could be higher than the other end. These are some of the reasons why 3-inch diameter ASMT A354 Gr BD anchor rods should have been subjected to surface hardness check at both ends, particularly because heat treaters were mainly concerned about passing the minimum tensile strength requirements, aiming at a higher hardness range (e.g., 35 – 37-HRC) than necessary.[41] In spite of this aimed hardness range, of 279 bars of 4140 steel (22' 7 3/4" long), 119 bars or 43% were reported to have 32-HRC as surface hardness and 120 bars (43%) 36 – 37-HRC as surface hardness. If the hardness was 32-HRC at the surface, the hardness at r/2 could be 30-HRC or lower, which would be equivalent to 138-ksi tensile strength or lower, potentially failing the minimum of 140-ksi tensile strength requirement for ASTM A354 Gr BD.

2.8 Alternate Materials for the Pier E2 Anchor Rods

The above problems, the hardness either being too high at the surface or too low at r/2, with 4140 steel came about because this grade has a relatively low hardenability. In Figure 11b, the hardenability of 4140 is compared against different low alloy steels, including 4340, which has higher concentrations of alloying elements than 4140. As a consequence, 4340 is more hardenable than 4140 and can produce a

[41] Gerdau MacSteel, HT No: M32854, WO No: 2285441, Customer specification: ASTM A354 Grade BD; Q&T; (Aim for 35 -37 HRC)Date: 7/13/09

flatter hardness traverse curve than that in Figure 10a. In other words, 4340 will have less problems with having surface hardness being too high for HE concerns and meeting the minimum tensile strength requirements of ASTM A354 Gr BD at the same time. Thus, anchor rods made of 4340 steel to the requirements of ASTM A354 Gr BD would tend to have surface hardness lower than those of 4140 steel and thus would be less prone to HE failures. The only problem is that 4340 is more expensive than 4140.

Alternatively, Caltrans could have avoided HE failures of the Pier E2 anchor rods if it had specified a lower strength anchor rod specification such as ASTM F1554, Grade 105.[42] The required tensile properties are compared against ASTM A354 Gr BD below.

	Tensile Strength, ksi	Yield Strength, ksi	Elonga-tion %	Reduction of Area, %	Hardness			
					minimum		maximum	
					HB	HRC	HB	HRC
ASTM A354 Gr. BD >2½ - 4 inches	140 min	115 min	14 min	50 min	293	31	363	39
ASTM F1554 Gr 105 ¼ - 3-inches	125 - 150	105 min	15 min	45 min				

The 150-ksi maximum tensile strength would be equivalent to 33-HRC maximum. In 3-inch diameter anchor rods, the surface hardness could go as high as 35-HRC whereas the hardness at r/2 could be 33-HRC. Still, ASTM F1554 Gr 105 has no restrictions on hot dip galvanizing.

2.9 Warnings Against Hydrogen Embrittlement in Hight Strength Steels

Hydrogen embrittlement failures of high strength steels are nothing new. They have been known for a long time and warnings about them are readily encountered in materials specifications and literature. Some examples are as follows.

Source	Warning Statement about Hydrogen Embrittlement
ASTM A354	NOTE 4—Research conducted on bolts of similar material and manufacture indicates that hydrogen-stress cracking or stress cracking corrosion may occur on hot-dip galvanized Grade BD bolts.
ASTM A490-97	5.4 Protective Coatings – The bolts shall not be hot dip, mechanically, or electroplated with zinc or other metallic coatings as such bolts are subject to hydrogen embrittlement with subsequent stress corrosion cracking and delayed brittle failure in service.
ASTM A490-12	Hot dip galvanizing is not permitted on A490 bolts because hot dip galvanizing may increase the material's susceptibility to HE during service.
ASTM A143[43]	In practice hydrogen embrittlement of galvanized steel is usually of concern only if the steel exceeds approximately 150 ksi (1100 MPa) in ultimate tensile strength.
ASTM F2329[44]	For high strength steel fasteners (having a specified minimum product hardness of 33 HRC), there is a risk of internal hydrogen embrittlement [IHE].

[42] ASTM F1554 Standard Specification for Anchor Bolts, Steel, 36, 55, and 205-ksi Yield Strength.
[43] ASTM A145 Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement

FHWA-SA-91-031[45]	"Hydrogen embrittlement after installation" is listed as one of fastener failure problems.
Numerous technical literature on hydrogen embrittlement including ASM Metals Handbook.	

2.10 Caltrans' Testing Protocol on Failed Anchor Rods

Figure 13 presents Caltrans' testing protocols on failed anchor rods. This was presented at the April 10 BATA meeting. In Figure 13, some wording has been changed because of a space problem while maintaing the same meaning.

The top sketch illustrates an acoustic test setup, which would presumably detect any crack initiation, growth, or both due to HE. Caltrans plans to do this on "10 selected samples" but did not say the basis of their selection. In the absence of any surface hardness data, Caltrans' selection of samples for acoustic tesing would have to be random, which is not desirable.

This testing is supposed to last for 30 days or 720 hours. No failures in this period do not mean no failures in the future as discussed before.

The following comments apply to the items listed under "Extended Testing Protocol."

(e)	Full load tests to failure will not provide any useful data for solving the HE failure problems.
(f)	For CVN tests, the notch orientation must be transverse to the anchor rod axis and parallel to the surface. The results will also dependent on the specimen locations such as the surface layer, r/2, and core. The specimens representing the surface layer should have a notch facing the center of the anchor rod so that the fracture area covers the outer layer of the anchor rod.
(g)	Tensile tests for three different loctions, surface, r/2, and core, may be less valuable than hardness traverse across the diameter.
(h)	Do hardness traverse tests using the Rockwell C scale rather than random hardness tests.
(i)	Chemical analysis of one location would suffice. Three locations within a cross section may be superflous as chemical segregations in a 3-inch diameter steel bar would be insignificant.
(j)	Scanning electron microscopy would be essential.
(k)	So is a microstructure evaluation
The note at the bottom of Figure 13 is largely inaccurate.	

2.11 Insitu Hardness Testing

Caltrans should conduct a 100% insitu hardness check on all anchor rods in Pier E2 using Equotip 3 portable hardness tester. The exposed threads outside the nuts may be used for this purpose as illustrated in Figure 14.

[44] ASTM F2329 – Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners

[45] US Department of Transportation, Federal Highway Administration, High Strength Bolts for Bridges, Report No. FHWA-SA-91-031, May 1991, Problem (VIII) Hydrogen Embrittlement after Installation, Slide 1-17.

2.12 Steel Collar Design

Figure 15 shows a conceptual steel collar design by Caltrans to hold a shear key to the Pier E2 cap beam. Shear Key S1 originally had 48 anchor rods and each one was tensioned to 570-kips or a total load of over 27,000-kips. For S1, 44% of the 48 anchor rods have already failed and rest is questionable if they would also fail due to EHE. Also, out of 16 anchor rods on one side of S1, 9 already failed. The steel beams, fingers attached underside the beams, and the studs to clamp the top and bottom beams together across the Pier E2 cap beam have to be very massive. It will be very difficult to utilize the "fingers" to substitute for the clamping force of the original anchor rods, particularly when the fact that the "fingers" must be a weldable grade is taken into consideration. This approach will not provide an equal substitute for the original design that utilized 3-inch diameter high strength steel anchor rods.

3.0 CONCLUSIONS

(1) The 3-inch dimeter high strength steel anchor rods in Pier E2 failed within days of tensioning due to the hydrogen embrittlement (HE) cracking mechanism. There are no other failure mechanisms that can account for the anchor rod failures in Pier E2.

(2) More specifically, 32 of the 96 anchor rods for shear keys S1 and S2 failed all in the bottom ends due to environmental hydrogen embrittlement (EHE) rather than internal hydrogen embrittlement (IHE). The former owes the failures to the hydrogen that enters the steel from the environment during service as a result of exposure to corrosive environments including the marine atmosphere in the San Francisco Bay.

(3) The most important factor in HE is the susceptibility of the steel to HE, not the hydrogen concentration or the stress. The higher the hardness (or the strength), the higher the susceptibility to HE. A maximum surface hardness should have been established for avoiding HE. Instead, Caltrans only limited the hydrogen entry into the steel during surface cleaning in preparation of hot dip galvanizing.

(4) The anchor rod supplier, Dyson, chose 4140 steel to manufacture the 3-inch diameter anchor rods to the requirements of ASTM A354 Gr BD and hot dip galvanized as specified by Caltrans. This grade of steel can have hardness at the surface higher than the 39-HRC maximum allowed for Gr BD and still be acceptable under the current ASTM testing protocol for hardness.

(5) Experience has shown that hot dip galvanizing increases the susceptibility of bolts and anchor rods to EHE failures during service. Therefore, for hot dip galvanized high strength steel anchor rods, Caltrans should have established a conservative hardness requirement, i.e., lower than the 39-HRC maximum required by ASTM A354 Gr BD, and should have specified the anchor rod surface as the hardness test location.

(6) Since long anchor rods can have different hardness from one to the other, Caltrans should have required a 100% surface hardness check at both ends of each anchor rod before hot dip galvanizing. Lack of these specific hardness requirements allowed anchor rods with surface hardness that was too high to be acceptable for use in the marine environment of the San Francisco Bay.

(7) The Pier E2 anchor rods failed due to EHE more because Caltrans neglected to establish the minimum requirements necessary for avoiding HE failures in high strength steel anchor rods than because hydrogen was allowed to enter the steel during manufacturing. The most important factor

in these HE failures is that the anchor rod steel was susceptible to HE because their surface hardness was too high, probably around 40-HRC or even higher.

(8) Material test reports from the anchor rod supplier (Dyson and its subcontractors) and those generated by Caltrans Testing Laboratory showed evidence that some of the Pier E2 anchor rods would have high surface hardness, and thus are susceptible to HE.

(9) It would be possible that some of the S1 and S2 anchor rods that have not failed and the S3, S4, and B1 - B4 anchor rods may fail during service in the years to come. Caltrans has no surface hardness data that may be used in judging whether or not any particular anchor rods need to be replaced rather than just waiting for them to fail sometime in future.

4.0 RECOMMENDATIONS

(1) Modify some of the post failure testing protocols because confirmation of hydrogen embrittlement as the failure mechanism is unnecessary and some of the proposed tests would be meaningless.

(2) Instead, conduct a 100% in-situ hardness check using an Equotip 3 or other portable hardness tester in the exposed threads outside the nuts, as illustrated in Figure 14. Compile the "surface hardness data" from all the anchor rods, including those that failed, in Pier E2 and evaluate the data with regards to the susceptibility of anchor rods to EHE (environmental hydrogen embrittlement).

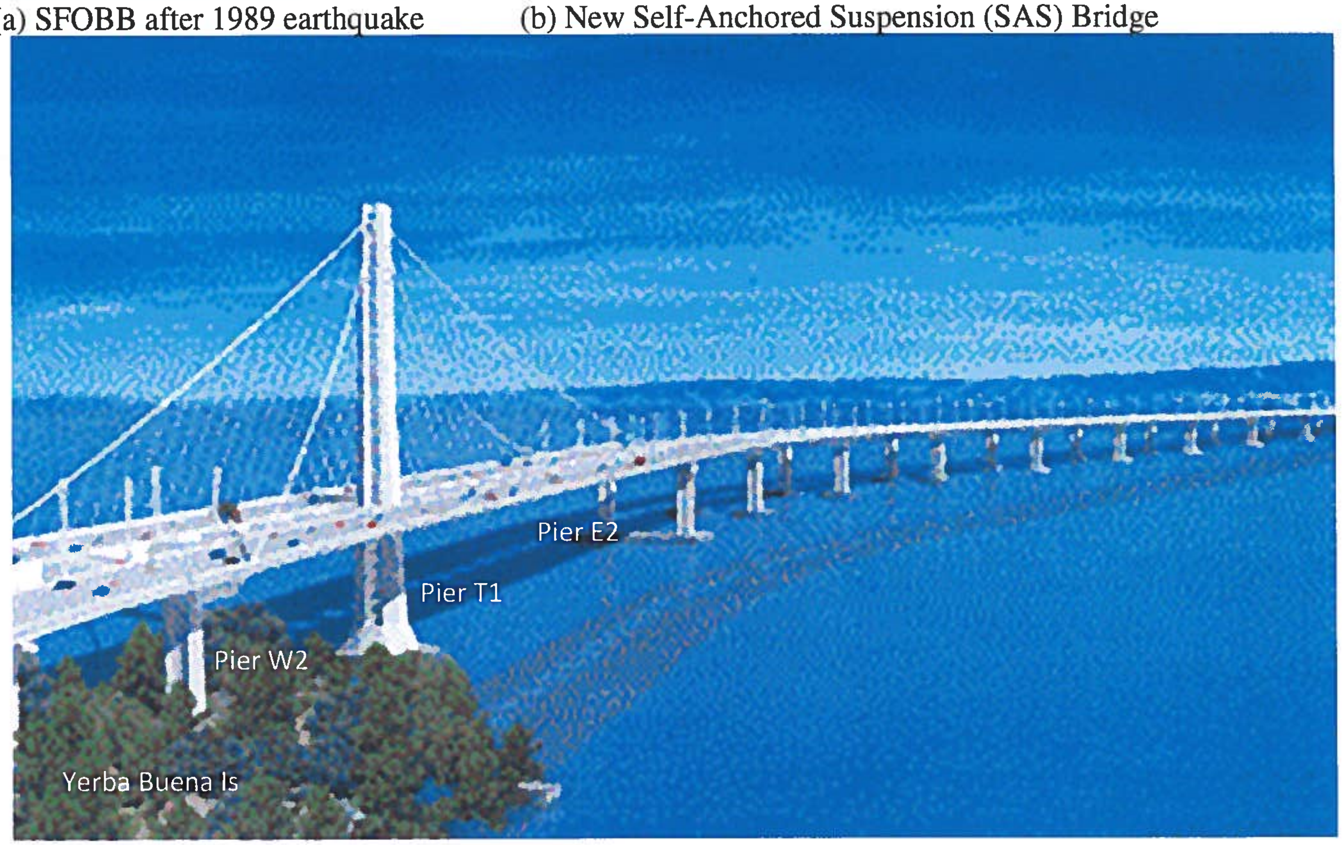
(4) Replace the anchor rods that are high in surface hardness, if possible.

(5) For replacement anchor rods, establish a maximum hardness limit for the anchor rod surface and require a 100% surface hardness check at both ends of each rod. Either the shank surface next to the end of the threads or three threads near the threaded ends as illusted in Figure 14 may be used for hardness test using an Equotip 3 or equivalent.

(6) Alternatively, consider specifying ASTM F1554 Gr 105, hot dip galvanized, for replacement anchor rods. Specify 33-HRC as a maximum surface hardness, not at r/2 or at the core.

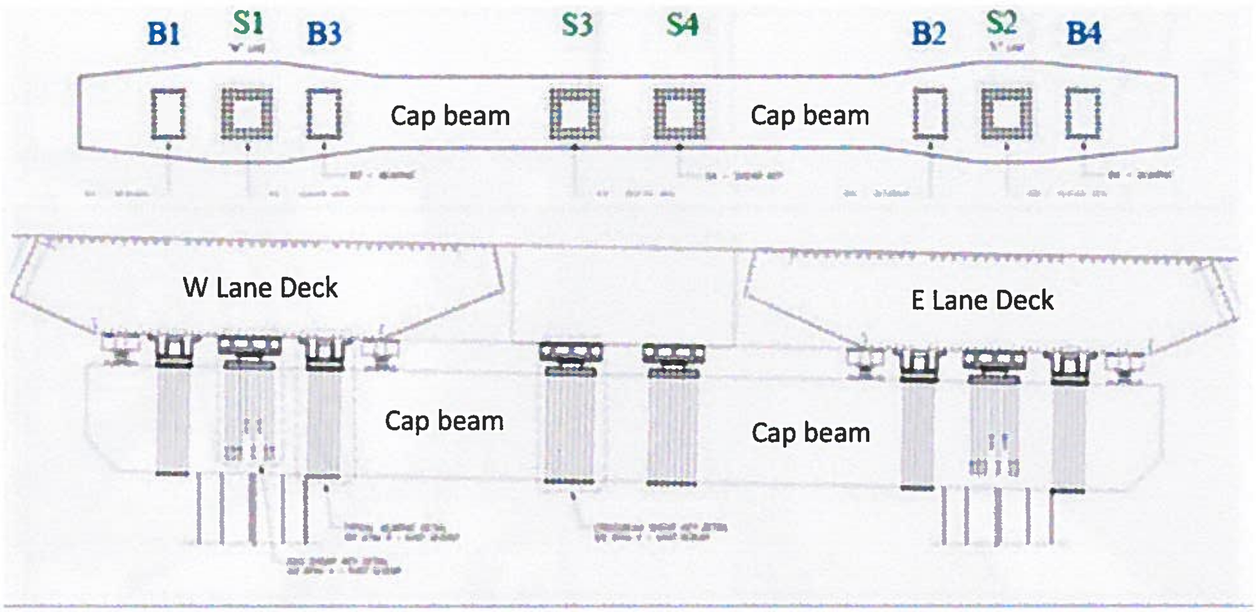
(7) If the same strength level (140-ksi min) as ASTM A354 Gr BD is required for replacement anchor rods, consider specifying 4340 as the material rather than 4140.

(a) SFOBB after 1989 earthquake (b) New Self-Anchored Suspension (SAS) Bridge

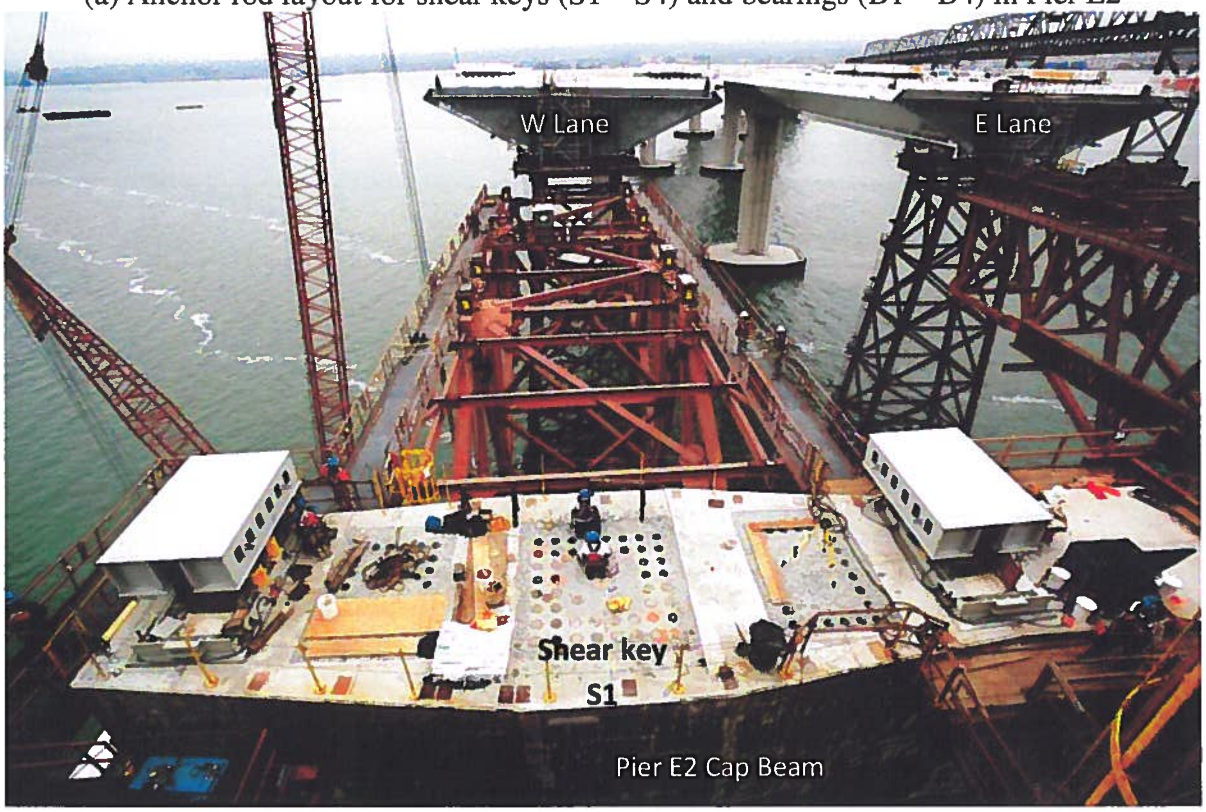


(c) Piers T1, E2, and W2 of SAS Bridge

Figure 1 (a) A new self-anchored suspension (SAS) bridge near completion with the old bridge to the east. (b) A view of the SAS Bridge, when completed, supported by Piers T1, E2 and E3.



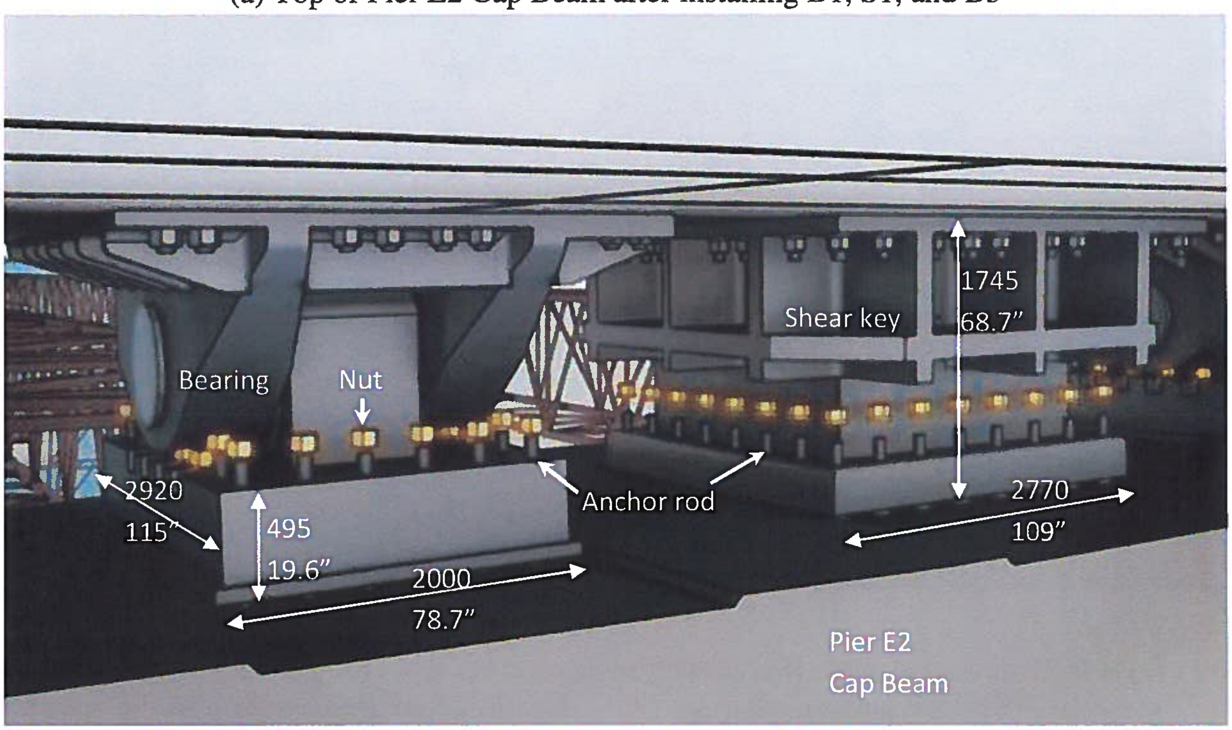
(a) Anchor rod layout for shear keys (S1 – S4) and bearings (B1 – B4) in Pier E2



(b) Top of the cap beam of Pier E2

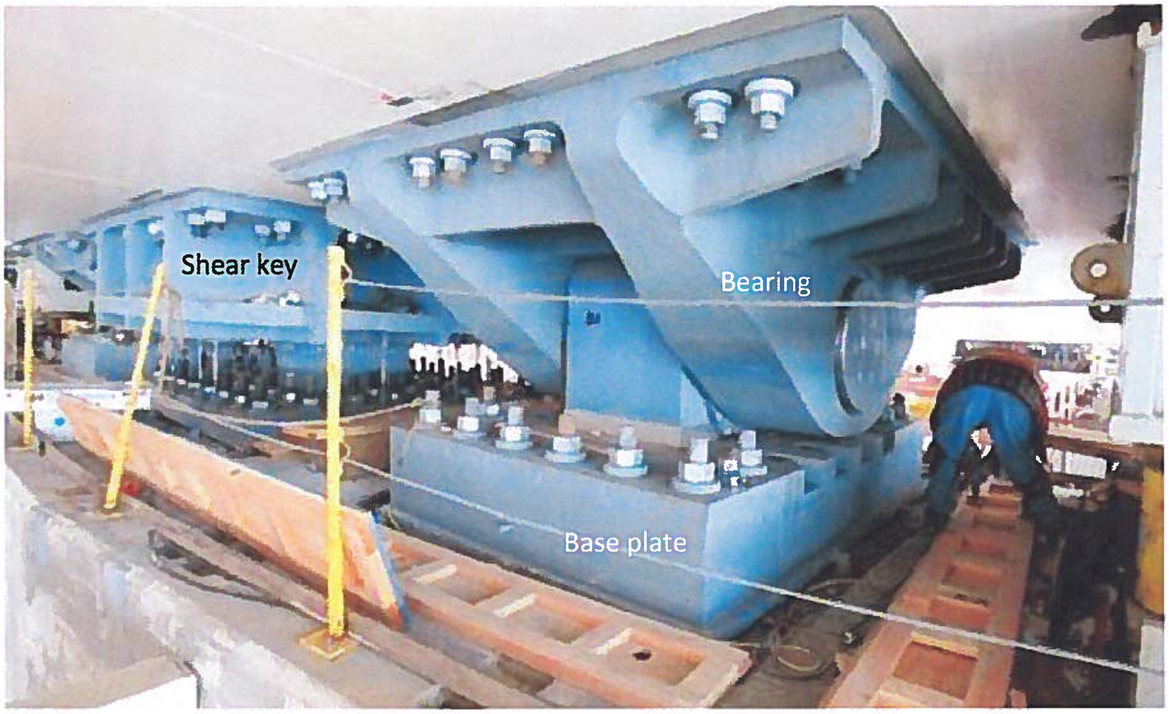
Figure 2 (a) Pier E2 top and elevation views with anchor rod locations through the cap beam for four shear keys (S1 – S4) and four bearings (B1 – B4). (b) Top of the cap beam before installing bearings B1 and B3 and shear key S1.

(a) Top of Pier E2 Cap Beam after installing B1, S1, and B3

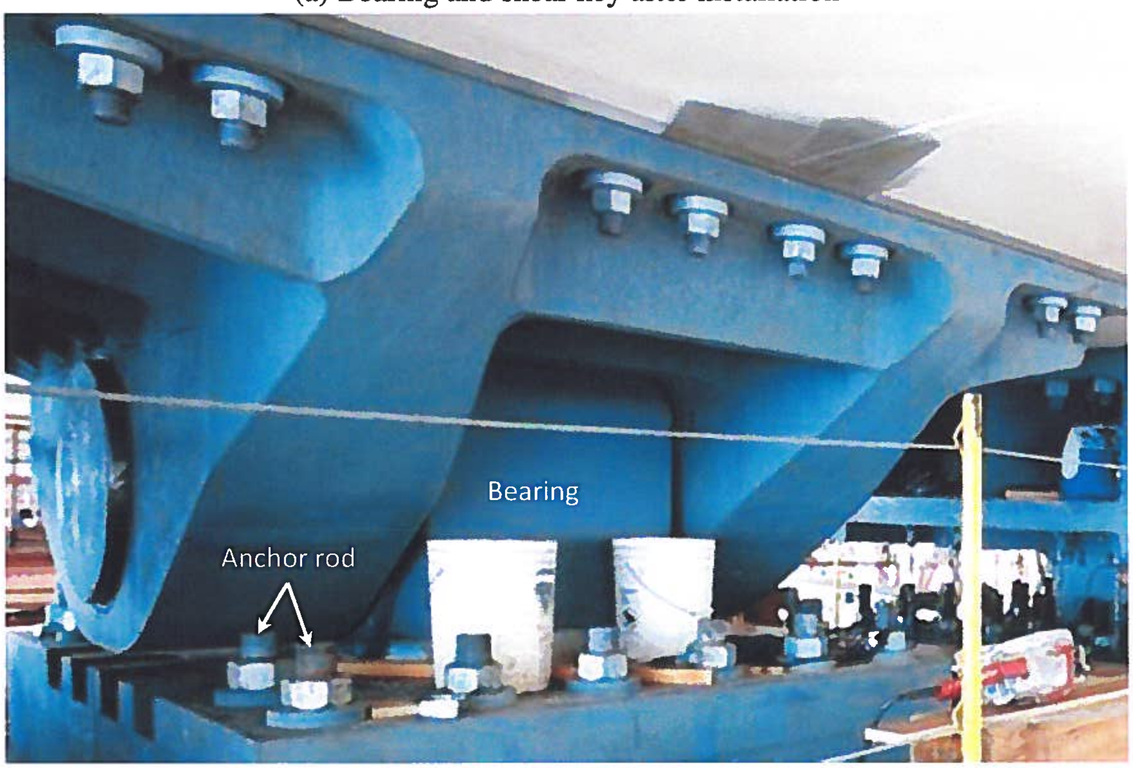


(b) Anchor rods in the thick base plates of bearing and shear key

Figure 3 (a) Top of Pier E2 Cap Beam after installing B1, S1, and B3. (b) An illustration of anchor rods ready for nut engagements.

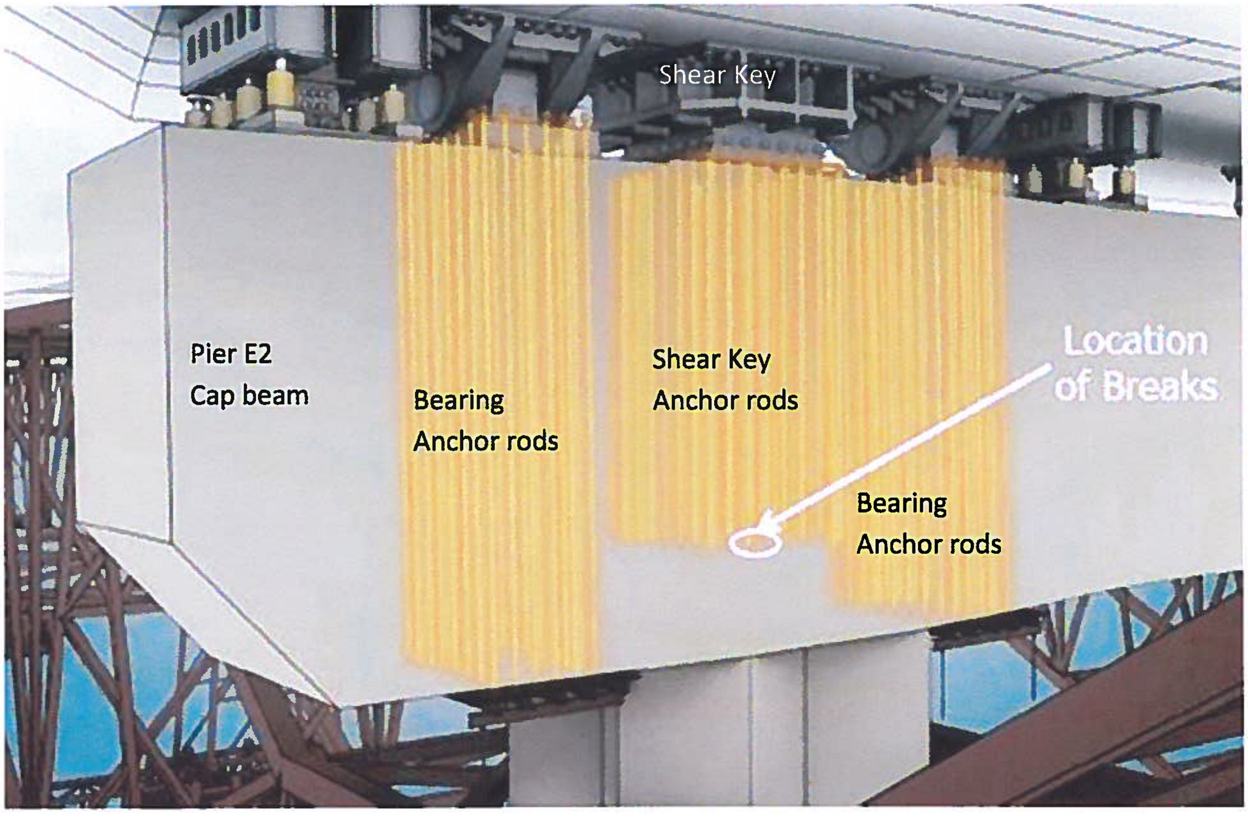


(a) Bearing and shear key after installation



(b) Bearing after anchor rod–nut engagement

Figure 4 Photographs of a bearing and a shear key after anchor rod installation.



(a) Anchor rods in the Pier E2 Cap Beam

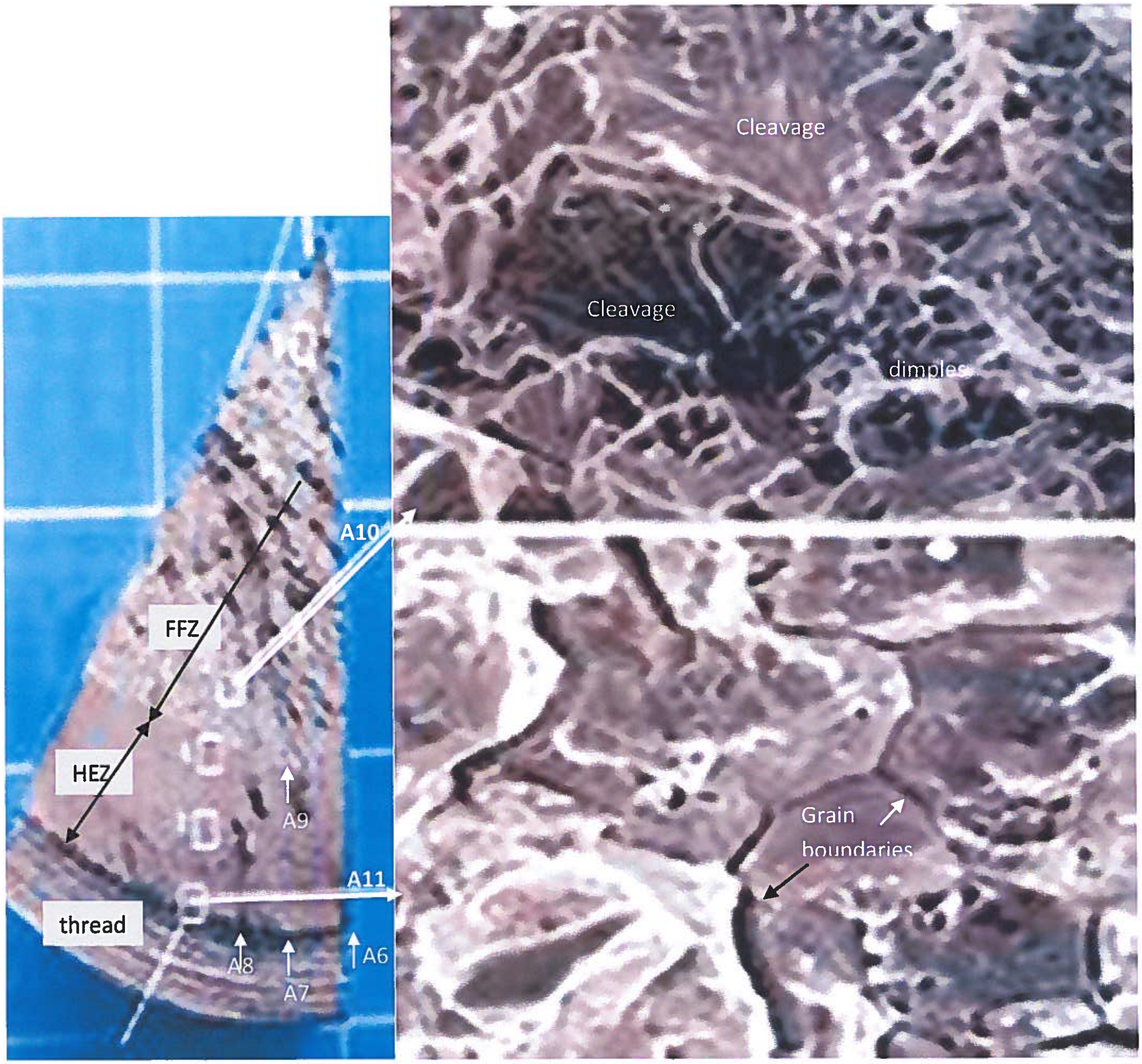
(b) Underside of the Pier E2 camp beam showing anchor rods for a bearing

Figure 5 (a) Top of Pier E2 Cap Beam showing the anchor rods for bearings and a shear key. Several anchor rods failed at the bottom ends. (b) Underside of the Pier E2 cap beam showing the anchor rods for a bearing.

(a) One of failed anchor rods on a shear key base plate

(b) Fracture face of a failed anchor rod.

Figure 6 (a) One of shear key anchor rods that failed at the bottom end. It popped up when the residual tension was released upon failure. (b) Fracture face of one of failed shear key anchor rods. The crescent area at arrows A1-A2-A3-A4 is marked HEZ (hydrogen embrittlement zone), which formed while the anchor rod was under static tension. The rest, FFZ (fast fracture zone), was formed almost instantly.



(a) Fracture face at arrow A6 (b) SEM micrographs at arrows A10 and A11 in (a)

Figure 7 (a) Enlarged view of the wedge at arrow A6 from the fracture face of a failed anchor rod in Figure 6b. Arrows A6, A7, and A8 point to ratchet marks, which resulted from multiple fracture origins. (b) Scanning electron fractographs of the HEZ (hydrogen embrittlement zone) at arrow A9 and the FFZ (fast fracture zone) at arrow A10. The fracture mode was predominantly intergranular for the HEZ and a mixture of cleavage and dimples for the FFZ.

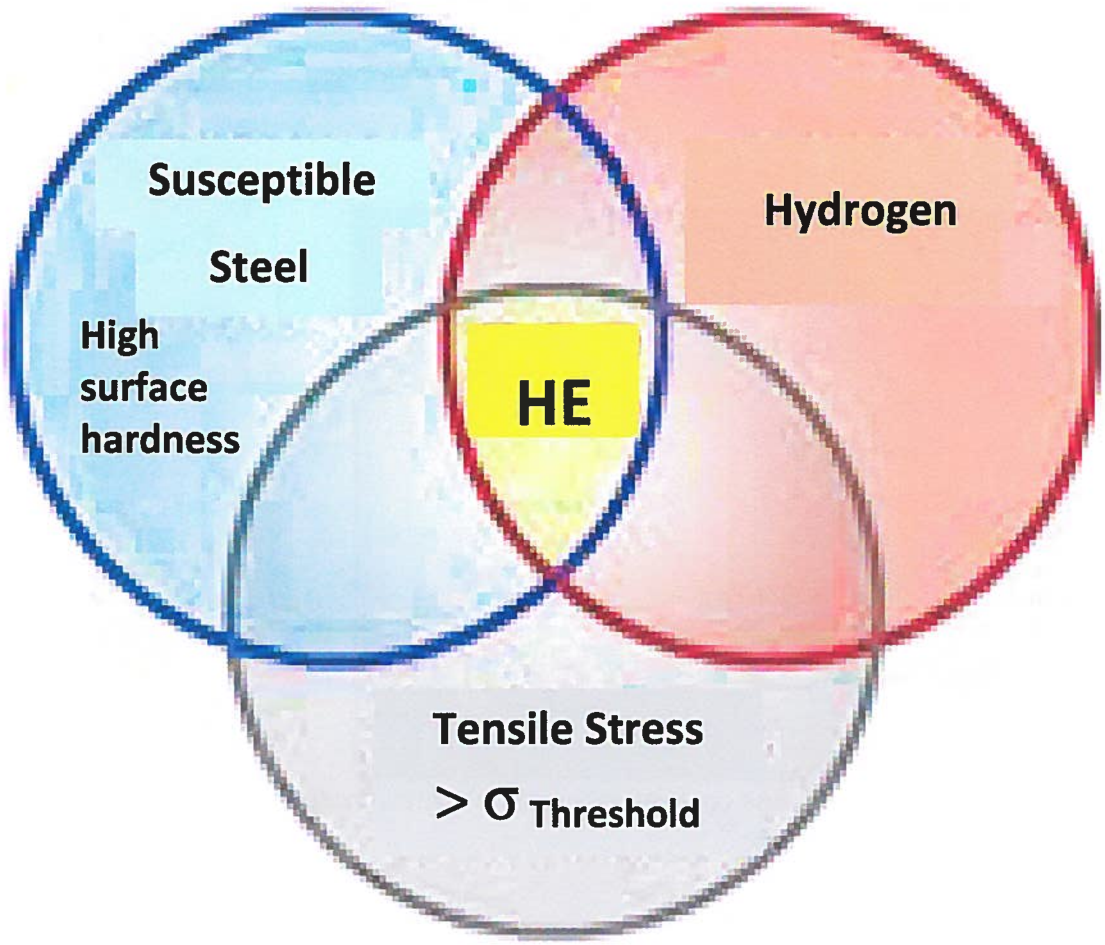
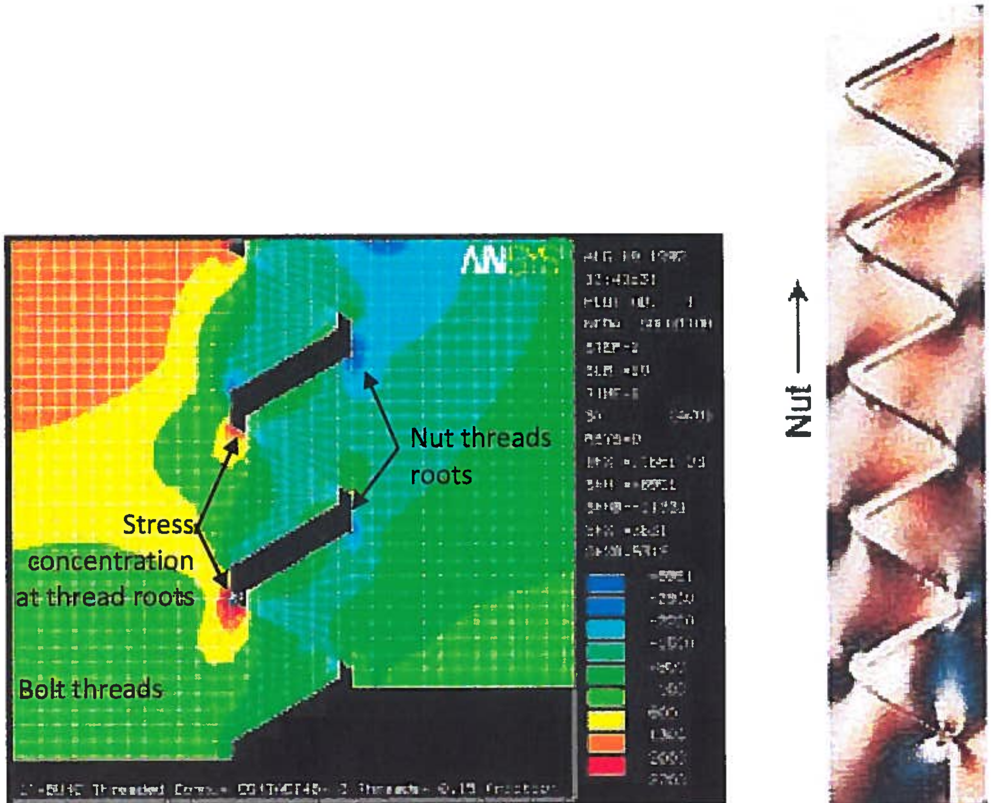
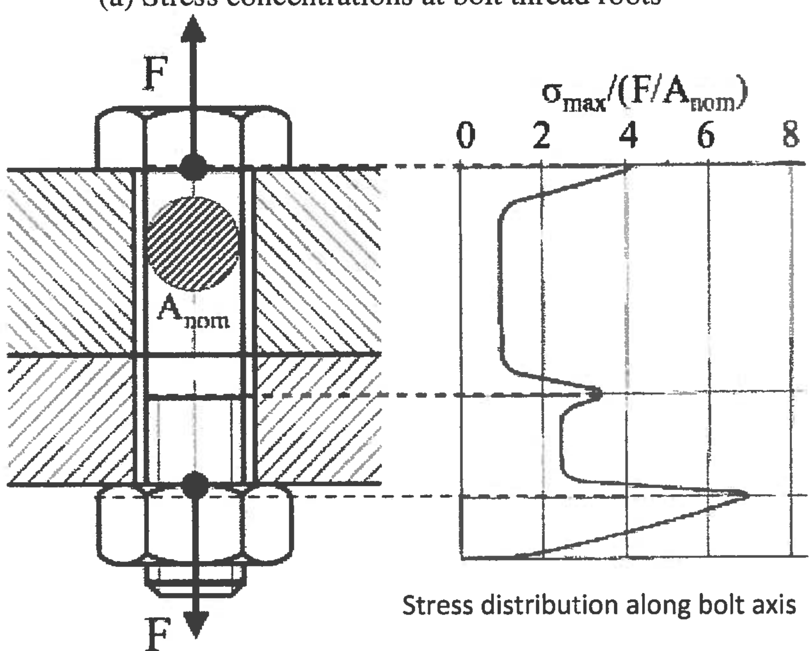


Figure 8 Tri-circles, depicting the three essential conditions required for hydrogen embrittlement (HE)[46]

[46] http://www.lambdatechs.com/documents/264.pdf



(a) Stress concentrations at bolt thread roots[47,48]



(b) Stress concentrations in a bolt under tension[49]

Figure 9 (a) Stress concentration effects at the roots of bolt threads under tension as a result of torqueing down the nut. (b) The root of the first engaged thread in the bolt would experience the highest stress when tensioned by a nut.

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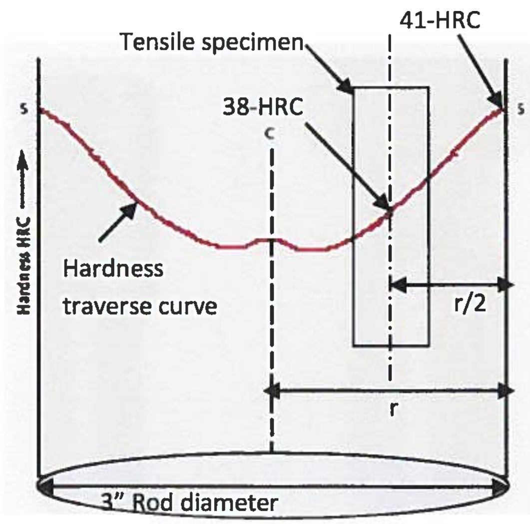
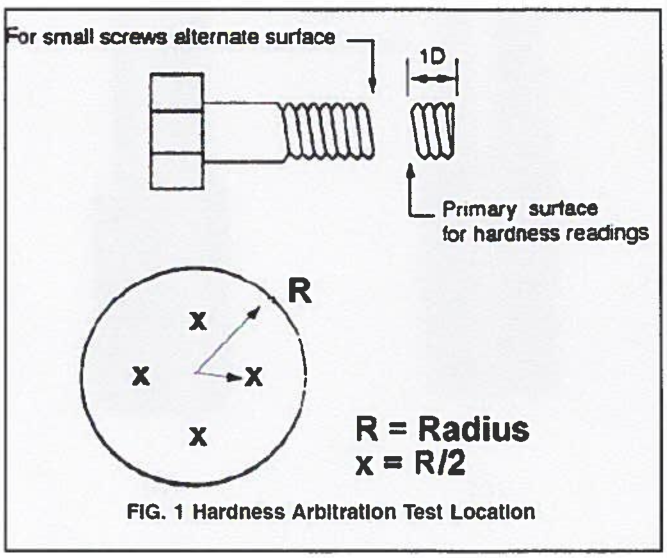
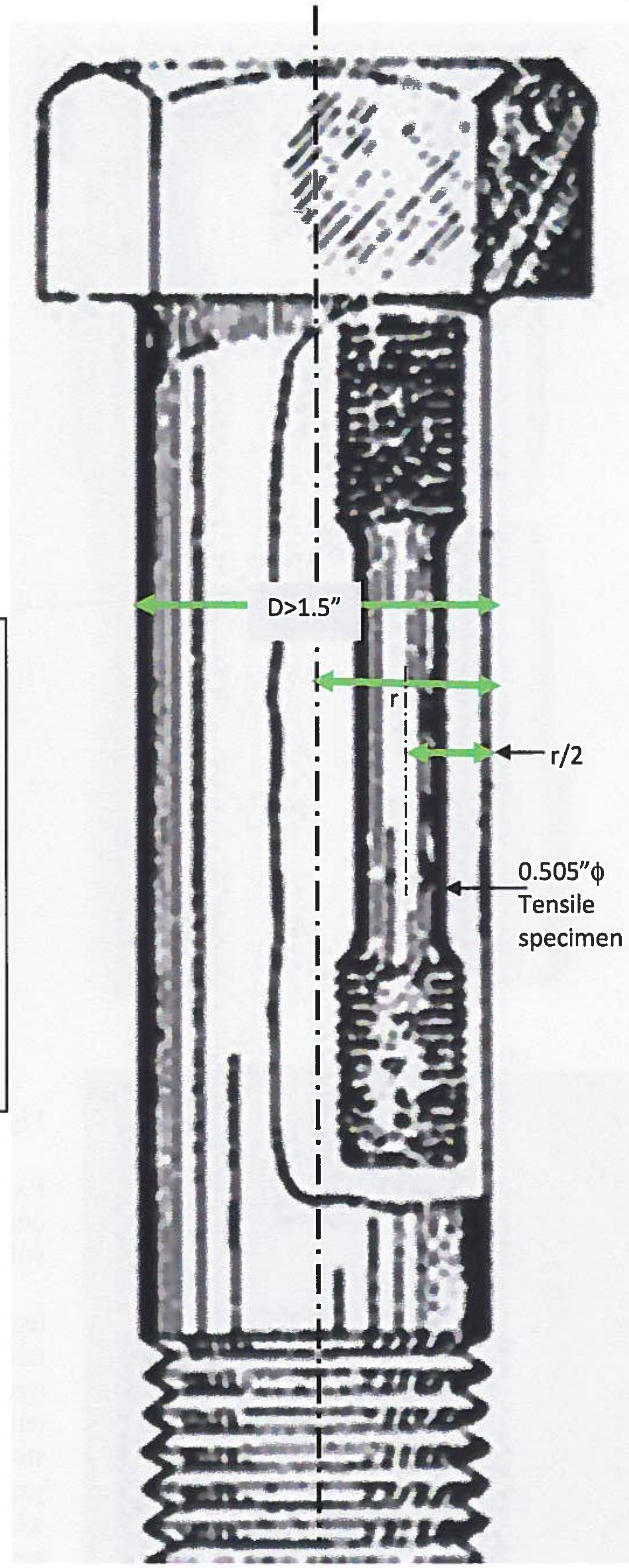
[47] engr.bd.psu.edu
[48] www.gizmology.net
[49] www.sciencedirect.com



(a) Exemplar hardness traverse curve for oil quenched and tempered 4140 steel



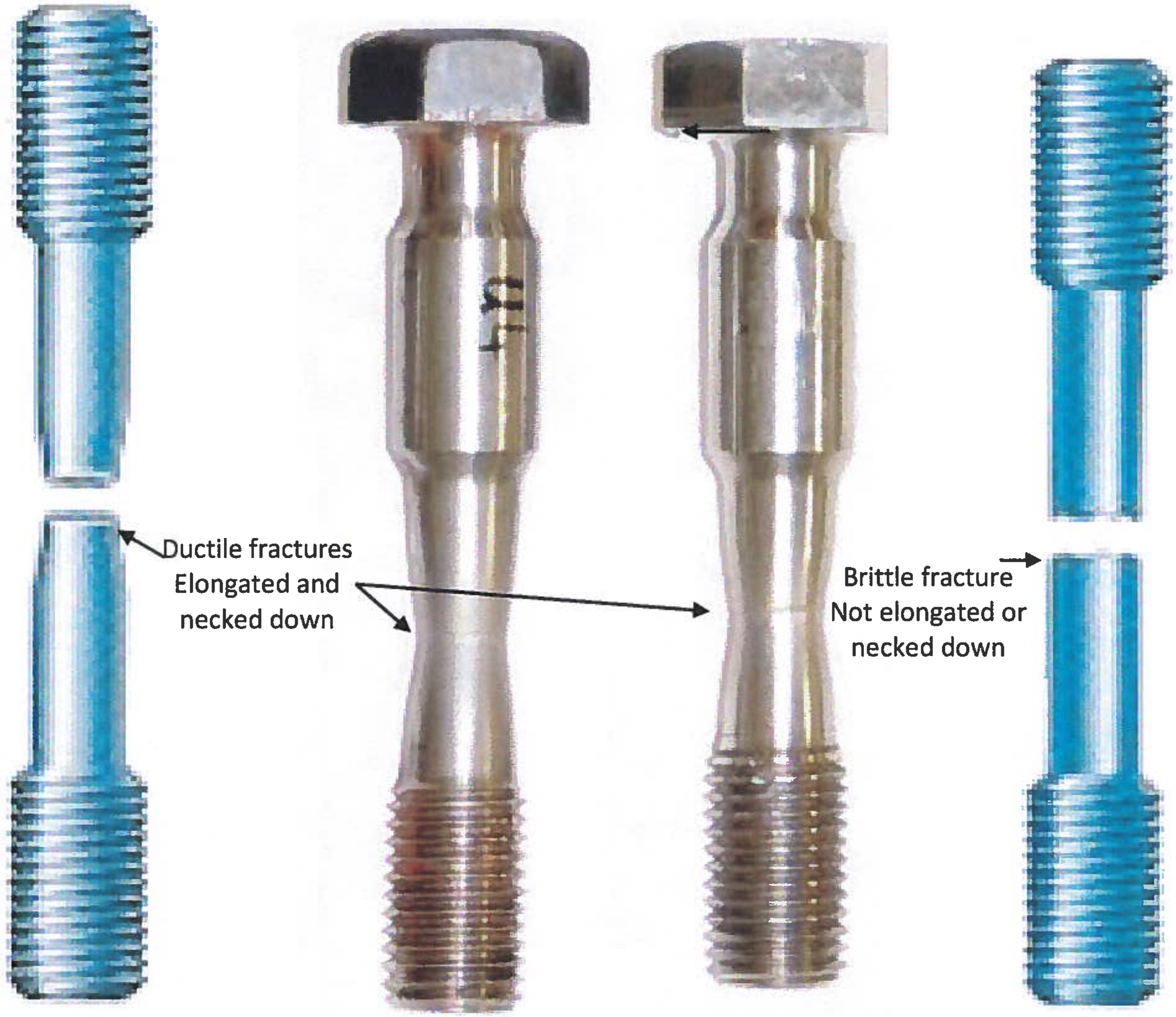
(b) Arbitration hardness test location per ASTM F606 and A370



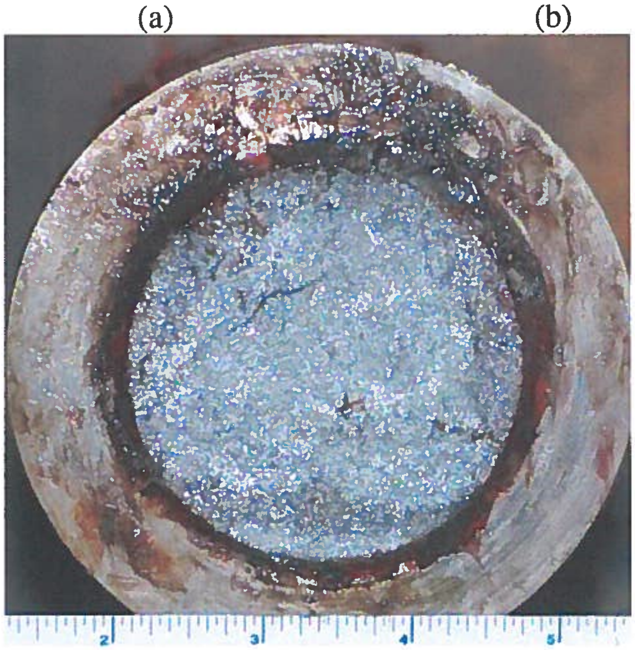
(c) Tensile specimen location at mid-radius per ASTM F606 and A370 for D>1½ inch

Figure 10
(a) Exemplar hardness traverse curve across a 3 inch diameter 4140 steel anchor rod, heat treated to meet the ASTM A354, Grade BD.

(b) & (c) Hardness and tensile test locations for steel fasteners including anchor rods in accordance with ASTM F606 and A370.



(a) (b) (c) (d)

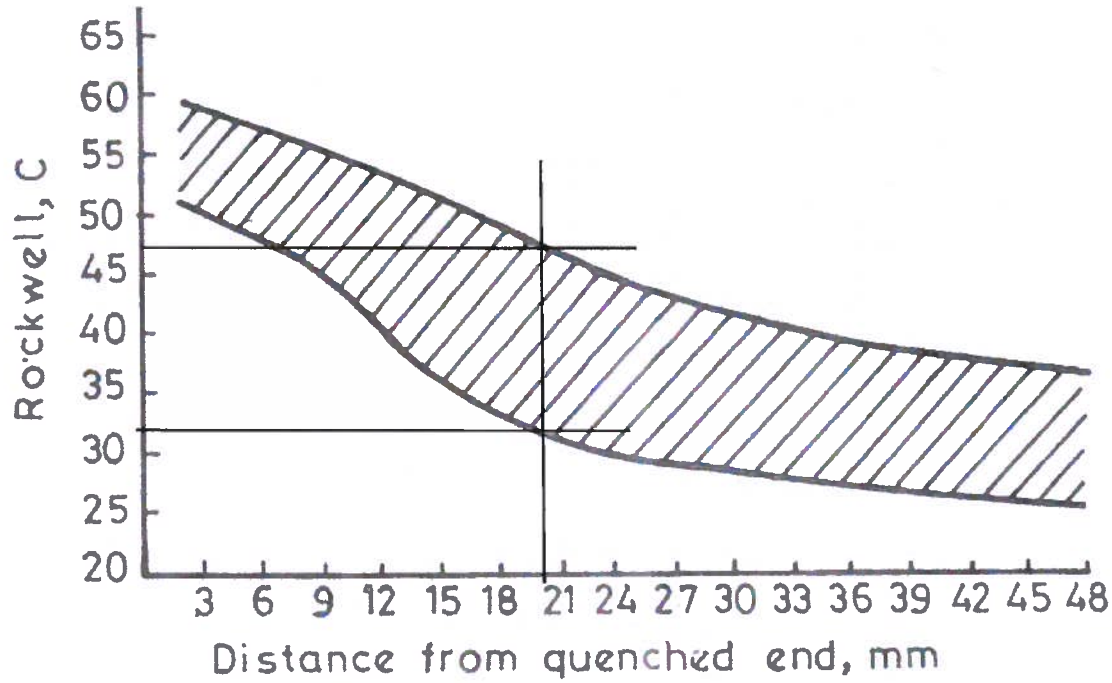


(e) Example of brittle fracture of a ductile steel

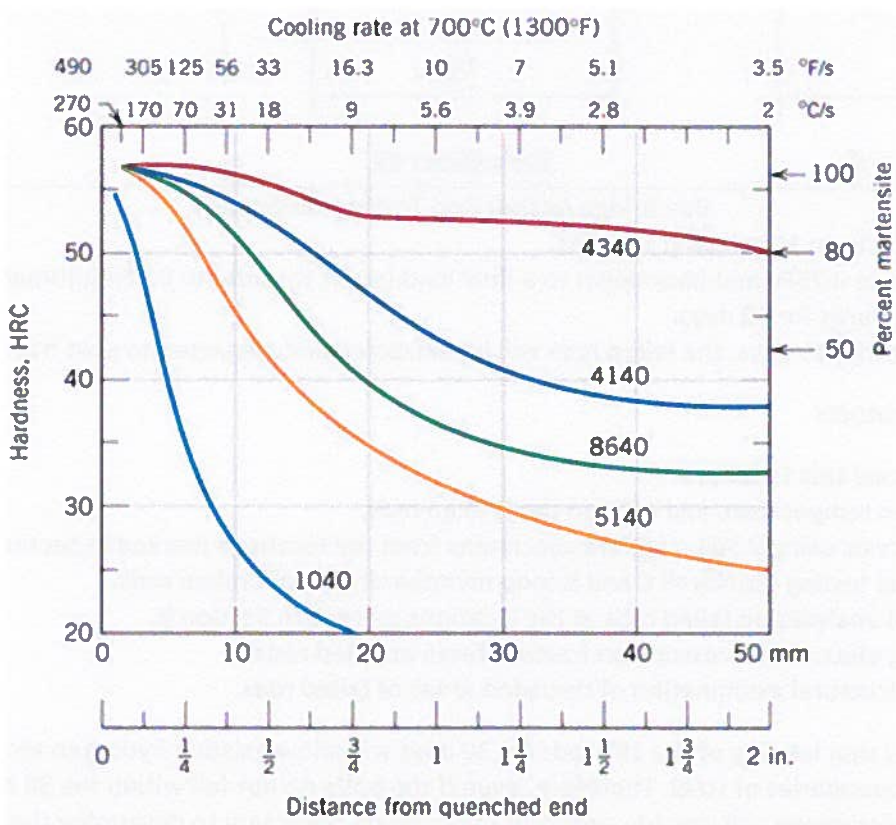
Figure 11

Examples of tensile specimens after testing showing ductile specimens in (a), (b), and (c) as compared with a brittle specimen in (d).

(e) shows the fracture face of a coupler pin between rail cars. The pin was made of 8620 steel in an as cast condition. It displayed a ductile behavior in tensile tests (80-ksi tensile strength, 45-ksi yield strength, 20% elongation, and 30% reduction area); yet broke in a brittle manner at a section change when overloaded due to an accidental bumping between rail cars one cold morning (around 40°F). The fracture started at the top and propagated down.

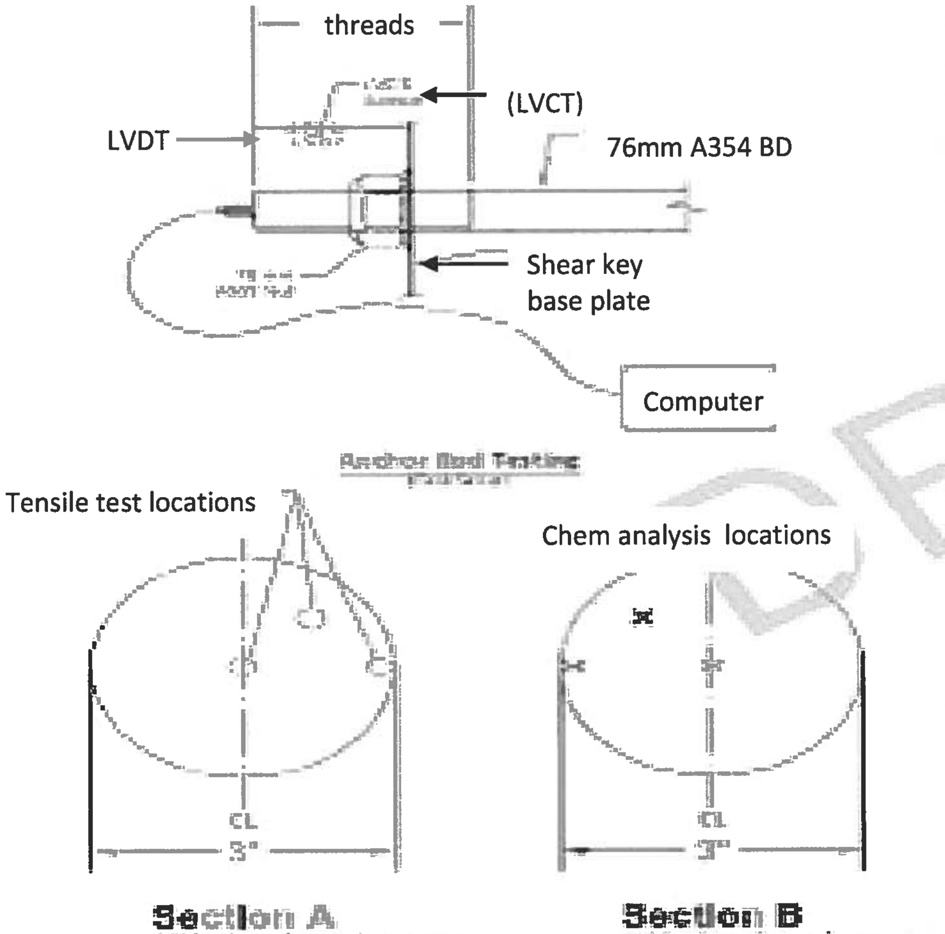


(a) Hardenability band for a low alloy steel similar to the 4140 steel



(b) Hardenability curves of different low alloy steels and a medium carbon steel.

Figure 12 Variability of hardenability within the same steel grade such as 4140 in (a) and different hardenability for different grades of low alloy steels and a medium carbon steel in (b).



Bay Bridge Anchor Rod Testing (Summary)

(a) In-situ acoustic tests on 10 selected samples.
(b) Load the 192 rod to 0.75Fu and back down to a final load (static tension) to 0.7Fu (ultimate tensile strength).
(c) Check daily for failures for 30 days.
(d) If any rod fails within 30 days, the failed rods will be extracted and subjected to post fracture analyses.

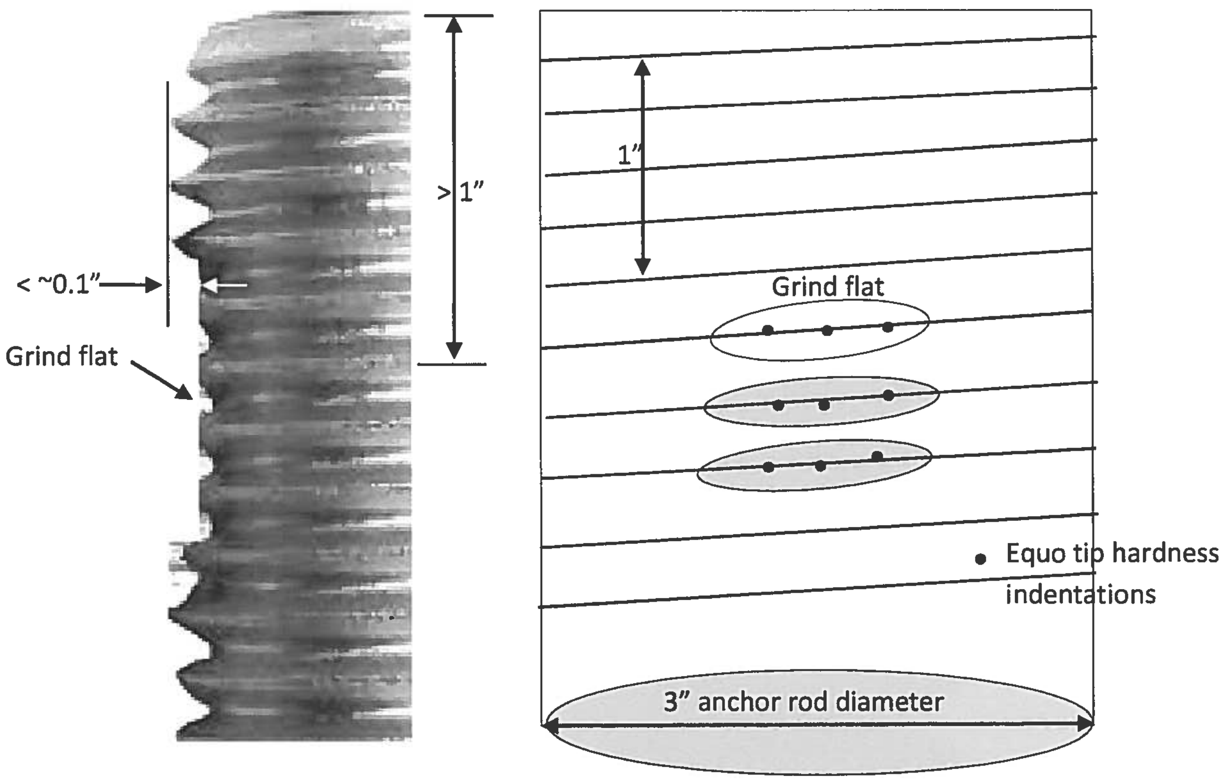
Extended Testing Protocol

(e) 10 samples full load test to failure
(f) CVN tests at room temperature and 40°F on the broken rods.
(g) Perform tensile tests using 0.505 standard specimens from the locations marked in Section A.
(h) Perform hardness testing (Rockwell C and Knoop microhardness) of broken rods.
(i) Perform chemical analyses on failed rods at the locations marked in Section B.
(j) Perform scanning electron microscopy on fracture faces of failed rods.
(k) Perform micro-structural examination of threaded areas of failed rods.

"Note: It is expected that loading of the 192 rods for 30 days will allow existing hydrogen atoms to propagate in between the grain boundaries of steel. Therefore, even if the bolts do not fail within the 30 day period, the scanning electron microscopy will provide sufficient information necessary to determine the presence of hydrogen."

Figure 13 Caltrans' testing protocols on failed anchor rods.[50]

50 http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2032/5_BATA_Oversight_April_10_2013_additional.pdf



(a) Exposed Threads (b) Ground flat spots on threads for hardness check

Figure 14 Equo tip hardness test location on exposed threads of anchor rods in Pier E2.

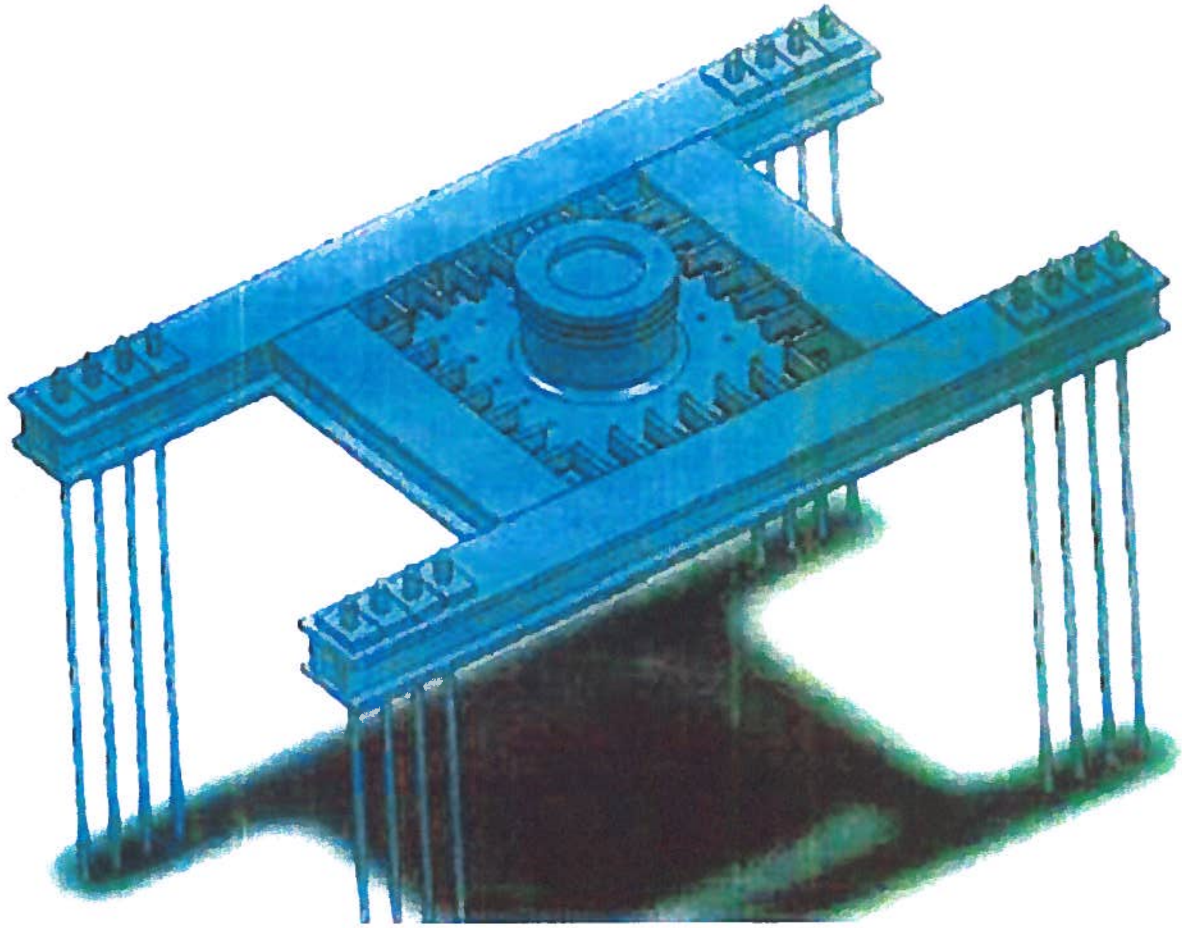


Figure 15 One of Caltrans' conceptual design of a "steel collar" to substitute for the failed shear key anchor rods.[51] "Fingers," seven per side, attached to steel beams, are supposed to clamp the shear key base plate down to the Pier E2 cap beam. Two shear keys, S1 and S2, each has 48 Grade BD anchor rods, 3-inch diameter. Of these, 21 failed for S1 and 11 for S2. One side of S1 had 9 out of two rows of 8 anchor rods failed and a total of 21 out of 48 anchor rods for S1 failed. Out of 48 anchor rods for S2, 11 failed, all due to hydrogen embrittlement in early March 2013.

[51] http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2032/5_BATA_Oversight_April_10_2013_additional.pdf

Yun Chung
201 Lagunaria Ln
Alameda, California

May 23, 2013

Department of Transportation
525 Burma Road
Oakland, CA 94607

Attention: Tony Anziano
Toll Bridge Program Manager

Re: Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6 by Brahimi et al.[1] Project# 04-0120F4, May 7, 2013

Dear Mr. Tony Anziano:

I have reviewed the report referenced above. My comments are presented on pages 3 – 17 of this file for your consideration.

The authors of the above report concluded that the Pier E2 anchor rods failed because of hydrogen embrittlement (HE). They did not, however, look for the environmental factors that could have been significant in the 32 anchor rod failures. No zinc coating evaluations were made at the failure locations, the bottom ends, or the top ends. Only two (S1G1 and S2A6) of the three failed anchor rod samples available for their metallurgical investigation were examined. Not even a hardness test was done on the third sample, S2H6. No photographs of its fracture face were presented. No explanations were offered as to why S2H6 could be ignored completely.

The authors mentioned that the three samples failed in the bottom ends but neglected to point out that all 32 failures occurred in the bottom ends. This is an important factor which was not part of the conclusions or "EXECUTIVE SUMMARY" of their report.

The authors suggested that the anchor rods failed because of internal hydrogen embrittlement (IHE) without laboratory data that can correlate specifically to the failed anchor rod samples. Instead, they tried to convey all 32 anchor rods failed because they were made of a "bad batch of steel" with "higher than normal susceptibility to HE." This appears to be based more on personal judgment than laboratory data that can correlate to any specified requirements in the specifications for the anchor rods.

Also, their metallurgical laboratory work was not diligent in several accounts. Some of their laboratory hardness and metallographic data, including Anamet data, need verification or validation.

One of important findings by the authors was that the failed anchor rods had hardness of 36 HRC near the surface, well below the 36 HRC required by ASTM A354 Grade BD. This finding would have an important implication on the disposition of the 2010 anchor rods for long term applications. This finding is, however, buried in the report; the authors did not discussed it, did not includ it in their "EXECUTIVE SUMMARY," and did not mention it in the conclusions. The hardness data, both Knoop and Rockwell C, however, seem to have some irregularities that would require further laboratory evaluation and validation.

[1] http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2047/7_E2_Shear_Key_Rod_Failure_Fracture_Analysis_Report.pdf

The report left several important questions unanswered. Thus, Conclusions 1 and 3 of the report needs to be supported by more lab data, technical references, or both. These and other concerns are discussed in the following pages, with recommendations at the end.

Sincerely yours,

Yun Chung

COMMENTS ON CALTRANS' METALLURGICAL REPORT ON PIER E2 ANCHOR ROD FAILURES

Table of Contents

COMMENTS ON CALTRANS' METALLURGICAL REPORT ON PIER E2 ANCHOR ROD FAILURES[2]

1.0 INTRODUCTION

1.1 Background of the 2008 and 2010 Anchor Rods

1.1.1 2008 Anchor Rods

The California Department of Transportation (Caltrans) specified ASTM A354 Gr. BD anchor rods for four shear keys (S1 – S4) and four bearings (B1 – B4) on Pier E2 of the new San Francisco-Oakland Bay Bridge.[3] All are 3-4UNC anchor rods in lengths up to 24-ft, manufactured by Dyson, grit blast cleaned, and hot dip galvanized. In 2008, 96 anchor rods for S1 and S2 were installed in the anchor rod ducts of the cap beam of Pier E2 at the eastern end of the self-anchored suspension (SAS) bridge. These 96 anchor rods for S1 and S2 are referred to as the 2008 anchor rods (or the 2008 bolts). They remained in the anchor rod ducts until early March 2013, when the ducts were filled with grout and the anchor rods were pretensioned to 0.7Fu (70% of the specified minimum ultimate strength or 0.7 x 140 = 98-ksi).

Within two weeks of the pretensioning, 32 of the 96 anchor rods for S1 and S2 failed, as follows:

Table 1

Breakdown of S1 and S2 Shear Key Anchor Rod Failures

Gerdau Heat No	Anchor rod size	# of Anchor rods installed		# of Anchor Rods failed		# of Failed Anchor Rods removed as of 3/13/2013		
	3" dia x	S1	S2	S1	S2		S1	S2
M644912	9' 11" long	18	18	3	3		0	0
M644914	17'2" long	30	30	18	8		2	2
Total		48	48	21	11	locations ➡	A7, G1	A6, H6
		96		32			4	

Both heats were produced by continuous casting from electric arc furnaces by Gerdau Ameristeel, St. Paul, MN. Their certified material test reports (CMTR) showed an identical chemical composition for both heats, as follows.

Table 2

Chemical Compositions for S1 and S2 Anchor Rods (referred to as the 2008 anchor rods)

HT #	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Sn
M644912	0.41	0.92	0.014	0.034	0.23	0.10	0.98	0.160	0.20	0.019
M644914	0.41	0.92	0.014	0.034	0.23	0.10	0.98	0.160	0.20	0.019

HT #	Al	V	Cb	Ca	Ti	Co	N	Zn	Hardness
M644912	0.001	0.030	0.003	0.0006	0.002	0.007	0.0102	0.001	293HB
M644914	0.001	0.030	0.003	0.0006	0.002	0.007	0.0102	0.001	293HB

[2] Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6 by Brahimi et al. Project# 04-0120F4, May 7, 2013
http://apps.mtc.ca.gov/meeting_packet_documents/agenda_2047/7_E2_Shear_Key_Rod_Failure_Fracture_Analysis_Report.pdf

[3] http://www.dot.ca.gov/hq/paffairs/AnchorRods/

Each melt of liquid steel of an electric arc furnace would constitute a heat number. A heat number is "an identifying number assigned to the product of one melting," similar to a birth certificate of a person. It is the foundation of quality control systems for steel product traceability to the steel mill where a unique number was originally assigned. Different heat numbers will have a different chemical analysis, which will invariably be different in some respects from other heats of steel of the same grade, say 4140 low alloy steel. The identical chemical composition for two different heat numbers is highly unusual.

To report an identical chemical composition for two heat numbers negates the basic purpose of the heat number system for steel product quality control. Dyson, Caltrans, or both should have determined why this unusual practice should be acceptable, condoned, or overlooked. After layer upon layer of QC/QA requirements, no one has flagged this anomaly. Even Brahimi et al merely reproduced the two identical chemical compositions, side by side in the same table, and made no comments about them in their report.[1]

TC Industries heat treated 25 bars, each 24' 1" long, and 70 bars, each 17'2" long, by oil quenching from 1600˚F, tempering at 1025˚F, and stress relieving (probably after straightening) at 925˚F. TC Industries showed hardness of 331 – 363 HBW (equivalent to 35 – 39 HRC) for [heat treat lot?] code MIS for the 25 bars, each 3" RD x 24'1" long, and 342 – 363 HBW (equivalent to 37 – 39 HRC) for [heat treat lot?] code MJF for the 70 bars, each 3" RD x 17'2" long. The former (25 bars) may have provided the 36 anchor rods, each 9'11" long, for S1 and S2, and the latter 60 anchor rods, each 17'2" long for S1 and S2, respectively.

1.1.2 2010 Anchor Rods

The rest of the 192 anchor rods for S3, S4, and B1 – B4 is referred to as the 2010 anchor rods, also manufactured by Dyson to the same requirements as for the 2008 anchor rods. The 2010 anchor rods all came from Heat Number M32854, produced by continuous casting from an electric arc furnace at the Gerdau MacSteel plant, Jackson, MI. They reported 32 – 37 HRC as "surface hardness" for four "batches" for a total of 269 bars, 3" RD x 22'7¾" long, Q & T (meaning quenched and tempered without specifying the temperatures and holding time), with the notation, "aim for 35 – 37 Rockwell C." Table 3, below, shows the chemical composition for Heat No. M32854 for the 2010 anchor rods.

Table 3

Chemical Compositions of Anchor Rods, referred to as the 2010 anchor rods

Heat No	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Sn
M32854	0.43	0.88	0.014	0.033	0.26	0.15	0.93	0.17	0.20	0.009

Heat No	Al	V	Cb	Ca
M32854	0.020	0.010	0.003	0.006

The 2010 anchor rods were installed in shear keys S3 and S4 and bearings B1 - B4 and pretensioned sometime in April 2013. No failure has been reported from them since then. Whether they were pretensioned to 0.7Fu or to a lower stress level such as 0.4Fu to avoid HE failures has not been clarified.

2.0 EVALUATION

2.1 Differences in Characteristics between the 2008 and 2010 Anchor Rods

Caltrans released some of the files related to the Pier E2 anchor rod failures in April 2013.[3] Chung reviewed these files and stated that hydrogen embrittlement (HE) was the only possible failure mechanism responsible for the Pier E2 anchor rod failures.[4] Brahimi et al also arrived at the same conclusion that the hot dip galvanized Gr. BD anchor rods in Pier E2 failed because of HE.[2]

So far, only the 2008 anchor rods failed. Caltrans and BATA[5] have been trying to dissociate the 2008 anchor rods from the 2010 anchor rods to support an idea that the 2008 anchor rods involved more "variables" and thus were more disposed to failures than the 2010 anchor rods. If anything, it was the other way around. As shown in Table 3 below, the 2010 anchor rods had more "variables" or more lot units than the 2008 anchor rods.

The characteristics of the 2008 anchor rods are compared against those of the 2010 anchor rods below.

Table 4

A Comparison between the 2008 and 2010 Anchor Rods in Pier E2

Characteristics	2008 Anchor Rods	2010 Anchor Rods	Difference Significant?
Steelmaker	Gerdau Ameristeel, St. Paul, MN	Gerdau MacSteel, Jackson, MI	No
Steelmaking	Electric Arc Furnace Continuous casting	Electric Arc Furnace Continuous casting	No
Reduction ratio	5.9 to 1	4.9 to 1	No
# of heats	2 HT M644912 (MIS) HT M644914 (MJF)	1 HT M32854	No, because M644912 and M644914 are identical.
# of [Heat treat lot] code	2 (MIS, MJF)	3 (NCJ10, NCJ11, NCJ12)	Probably yes, depending on lot definitions[6]
# of anchor rods	96 MIS 36 – 3" x 9' 11" MJF 60 – 3" x 17' 2"	192 96 – 3" x 21' 10.84" 32 – 3" x 22' 2.81" 64 – 3" x 22' 7.73"	
Heat treated by	TC Industries (Q & T & SR)	Gerdau MacSteel (Q & T)	Probably yes
HD Galvanizing by	Art Galvanizing	Monning Industries	No
Hardness, HRC	MIS: 35–39; MJF:37-39	32 – 37 for Batches 1 - 4	Yes
Exposed to wetness	Bottom ends for 5 yrs	Moist air for several mo.	Yes
Failure location	All 32 in the bottom ends	No failures	Yes

[4] Y. Chung: SAS Pier E2 Hot Dip Galvanized Grade BD Anchor Rod Failures, April 21, 2013, Prepared for Amy Worth, Metropolitan Traffic Commission.

[5] BATA – Bay Area Toll Authority

[6] The lot definition of ASTM A354 is interpreted or applied differently by different organizations.

The salient differences that set the 2010 anchor rods apart from the 2008 anchor rods are in the last three items in the above table: hardness, exposure time to wetness, and failure/no failure. The above comparison between the two groups of anchor rods does not support the "premise" that the 2008 anchor rods had more variables and, therefore, more probability of failures than the 2010 anchor rods.

Chung discussed the variability of hardness of 3-inch anchor rods of 4140 alloy steel that were hardened and tempered.[4] The 3-inch 4140 steel cannot achieve uniform hardness across the diameter. A hardness traverse across the diameter would typically look like a bowl, indicating high hardness near the surface and low hardness around the center (or core). In spite of this very basic fact that the hardness is test location sensitive, there is no uniform practice in hardness testing with respect to the test locations. For example, hardness is referred to as "surface hardness" by Gerdau and "core hardness" by TTML (a testing lab for Dyson).

More often than not, test reports, including those of Caltrans' testing laboratory, do not mention the test location of hardness. In spite of these uncertainties, a general trend was that the 2010 anchor rods had a hardness range (32 – 37 HRC) that was lower than those (35 – 39 HRC) for the 2008 anchor rods. BATA's Heminger presented averaged hardness/strength data that seemed to support that the 2008 anchor rods were higher in hardness and tensile strength than the 2010 anchor rods. The source of his data are unknown, however.

2.2 Hardness Data in CMTR

The 288 Gr. BD anchor rods in Pier E2 comprise 96 for shear keys S1 and S2, referred to as the 2008 anchor rods, and 192 for shear keys S3 and S4 and bearings B1 – B4, referred to as the 2010 anchor rods (Table 4). As discussed above, one of the most salient differences between the two may be hardness. This premise, however, still needs to be verified by in-situ hardness testing of all anchor rods in Pier E2.

In July 2009, Gerdau MacSteel shipped 3-inch round bards of ASTMA354 Gr BD, quenched and tempered to a target hardness range of 35 – 37 HRC. All were 22' 7 ¾" long. CMTR showed the following hardness and tensile property data.

Table 5

Summary of Hardness and Tensile Property Data from
Gerdau MacSteel CMTR for the 2010 Anchor Rods

		Surface Hardness HRC, as reported	UTS ksi As reported	HRC conv From UTS
Batch 1	100 bars	36	157.8	35
Batch 2	119 bars	32	155.6	35
Batch 3	40 bars	35	158.2	35
Batch 4	10 bars	37	153.0	34
Total	269 bars 3" dia x 22' 7 ¾" long			

The above table shows inconsistency in the hardness data: the surface hardness is not the same as the hardness numbers converted from the UTS (ultimate tensile strength) data. It is apparent that a single surface hardness, 32 HRC, for Batch 2 of 119 bars may not mean that all individual bars will have 32 HRC when tested at the circumferential surface. Since the tensile specimens are usually machined from a mid-radius location, the 35 HRC there would contradict the 32 HRC at the surface. This inconsistency is not really a problem, however. This is because another bar from the same batch would likely show a different hardness number, which would be still within the requirements of ASTM A354 or 31 – 39 HRC. This rather wide range of hardness is specified primarily because of the recognition that hardness of individual bolts and anchor rods would vary from one to another.

The size of the anchor rods in Pier E2, 3-inch diameter and each weighing several hundred pounds, presents a problem which is not a problem with bolts of smaller sizes, each around a pound or less.[7] Not only the hardness can vary from the surface to the core and from one bar to another within the same "batch" or "lot" but also it can vary from one end to the other end of the same bar. These hardness variations would be expected of a 3-inch diameter 4140 steel bar that is 10', 17' or 22' in length. This is one of main reasons why Caltrans should have required each anchor rod be hardness tested for the shank surface next to the ends of the threads at both ends.

Brahimi's report contained Anamet's Rockwell C hardness data on three cross sections from S1G1 and S2A6. [8] The results may be summarized as follows.

Table 6

Summary of Anamet's Rockwell C Hardness Data on S1G1 and S2A6 Cross Sections[9]

	HRC, Rockwell C		
	S1G1-11 Threaded	S2A6-2 Shank	S2A6-12 Threaded
Surface	37 - 37	36 - 36	37 - 38
1/2 R	32 - 35	33 - 36	33 - 36
Center	30	30	30

Brahimi et al did not include the hardness data of S2A6-2 from the top end in their report. When compared with the hardness data of S2A6-12 (bottom end), the surface hardness of 36-HRC of the former is lower than 37 – 38 HRC of the latter, both from the same anchor rod, which was 17' 2" long when installed. This is an example that would support the above discussion that the 3 inch anchor rod can vary in hardness from one to another.

The above table points to a very important revelation: the failed anchor rods had surface hardness of 36 – 38 HRC, which were lower than the 39 HRC maximum required by ASTM A354 Gr BD. This is an important data that indicate that the "Engineer" must exercise precautions beyond the requirements of standard specifications. This could have occurred specifically because the Pier E2 anchor rods were hot dip galvanized, which increased the susceptibility to HE, and the 2008 anchor rods sat in anchor rod ducts for five years during which they were exposed to the marine atmospheric conditions. Brahimi et al mentioned the possibility of hydrogen entry during this five year period. They did not treat this as an important factor and failed to look for evidence of zinc coating corrosion in the bottom ends where all 32 failures occurred.

[7] A 3" dia x 20 ft steel bar would weigh about 400 pounds.
[8] Reference 2 (Brahimi et al), Figure A10.
[9] Reference 2 (Brahimi Report), Appendix B.

2.3 Maximum Hardness Limit for Avoiding Hydrogen Embrittlement

If the 96 of the 2008 anchor rods and the 192 of the 2010 anchor rods had been subjected to hardness tests individually at the shank surface next to the top threads, the results would look like the two curves in Figure 1, below.

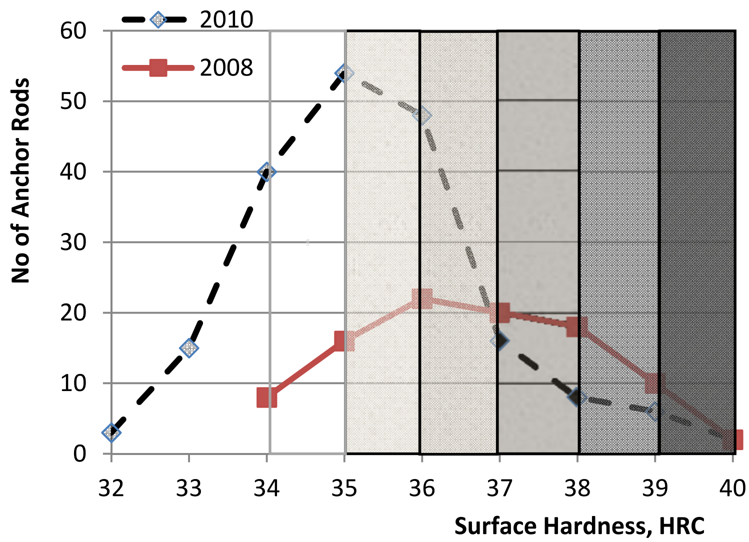


Figure1 Hypothetical hardness distribution curves for the 2008 and 2010 anchor rods.

The above distribution curves are hypothetical because they are based on imaginary hardness data, not actual data.

The 3-inch Gr. BD anchor rods in Pier E2 has 4 UNC threads with a minor diameter of 2.702-inches. Thus, the thread roots are 0.149-inch deep. The hardness at this location would be about the same as that for the shank surface. This surface location is significant because HE cracks will initiate at the root surface of the first thread that was engaged by the nut because the stress will be higher there than any other location along the anchor rod length.

If Caltrans has actual hardness data for individual anchor rods in Pier E2, they have not released them to the public. Using the surface hardness as a criterion, Figure 1 shows hypothetical hardness distribution curves for the 2008 and 2010 anchor rods. Had Caltrans taken a complete inventory of surface hardness, using a portable hardness tester, the results will be similar to Figure 1.

Low alloy steel that has been quenched and tempered is commonly referred to as LAQTS. Alloy 4140 is perhaps the most widely used LAQTS. The anchor rods in Pier E2 are made of 4140 steel, quenched and tempered. Therefore, they are all LAQTS.

Experiences with LAQTS have shown that it can fail due to HE when the hardness was high. To avoid HE failures, ASTM A354 limits the hardness to 39 HRC maximum and A490 to 38-HRC. A general consensus exists on the validity of the maximum hardness limit at 38 – 39 HRC for avoiding failures due to HE during atmospheric services. This is indicated by the darkest shade in Figure 1. Again, based on empirical data, the susceptibility of LAQTS to HE has been known to decrease with hardness below 39 to 40 HRC as depicted by progressively lighter shades in Figure 1.

As demonstrated by the S1 and S2 anchor rod failures, LAQTS with hardness lower than 38 HRC can failed due to HE. Hardness as low as 350 HK (equivalent to 35 HRC) was reported by Brahimi et al for near the surfaces of S1G1 and S2A6 and 36 HRC for the shank surface of S2A6 by Anamet. If these hardness numbers can be validated to be accurate, this would be a very troubling finding for Caltrans. This is because the surface hardness of 35 to 36 HRC for the S1 and S2 anchor rods that failed could mean that even the 2010 anchor rods with hardness higher than 35 to 36 HRC at the surface could fail due to HE during service in the San Francisco Bay in the years to come. Individual anchor rods that are happened to have surface hardness higher than 35 – 36 HRC are potential HE failure candidates during service regardless whether they belong to the 2008 group or the 2010 group of anchor rods. Average hardness values or average tensile strength values would be no help for the individual anchor rods that are high in hardness. This is why it would be a fallacy for Caltrans to try to buy off the entire 2010 anchor rods based on some average hardness/strength data what are lower than those for the 2008 anchor rods.

Below 33 HRC, LAQTS will not fail because of HE. This is validated by several documents, for example,

ASTM A143[10]	In practice hydrogen embrittlement of galvanized steel is usually of concern only if the steel exceeds approximately 150 ksi (1100 MPa) in ultimate tensile strength.[11]
ASTM F2329[12]	For high strength steel fasteners (having a specified minimum product hardness of 33 HRC), there is a risk of internal hydrogen embrittlement [IHE].

These warnings about HE failures for LAQTS with hardness above a certain limit were echoed by Fisher when he was quoted in the San Francisco Chronicle on May 21, 2013 as saying,

> "Caltrans needs to examine hundreds of at-risk rods on the new eastern span of the Bay Bridge and replace any that are hard enough to be vulnerable to cracking, says an internationally known expert who serves as an adviser to the state agency."[13]

Obviously, Fisher was referring not only to the Pier E2 anchor rods but also to other LAQTS bolts, some as large as 4 inches in diameter, in the tower and elsewhere in the new San Francisco Bay bridge. According to the SF Chronicle, Fisher would cut off at 34 HRC and any LAQTS bolts and anchor rods with hardness higher than 34 HRC would have to be replaced. This would essentially limit the acceptable hardness range to 31 to 34 HRC for ASTM A354 Gr BD anchor rods. It is doubtful if bolt manufacturer will be willing to produce 3-inch LAQTS anchor rods to this tight hardness range requirement.

[10] ASTM A145 Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement

[11] 150 ksi tensile strength is equivalent to 33 HRC in hardness.

[12] ASTM F2329 – Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners

[13] http://www.sfgate.com/bayarea/article/Expert-Replace-at-risk-Bay-Bridge-rods-4532939.php
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3.0 Review Comments on Metallurgical Failure Analysis Report by Brahimi et al[2]

The failure analysis report by Brahimi et al on the failed S1 and S2 anchor rods contain simple errors as well as certain technical deficiencies. They are discussed below.

3.1 Comments on Errors and Simple Technical Issues

(a) Simple Errors		
p.2	Executive Summary "When the specified tensile strength exceeds …"	Should read "When the actual or measured tensile strength exceeds …"
p.6	A. Knoop Microhardness "from 297 KHN to 446 KHN"	The correct designation is HK, not KHN. All knoop hardness values should show the load used. Ex $297HK_{500}$, indicating a 500 gram load was used.
p.9	Table 3 Note 1: heat No. M058938 is incorrect. Note 2: heat No. M058925 is incorrect.	 The correct HT No is M644912. The correct HT No. is M644914.
	Photo 25 "in grain direction."	Should be "in grain flow direction" or "in rolling direction."
	Table 1 "Location, Depth from surface"	This should be "depth from the thread root" which is already 0.149 inch from the [original] shank surface.
	Table 4 "Location, Depth from surface"	This should be "Location along thread profile" without (in).
(b) Statements that require clarification		
p.2	Executive Summary "The metallurgical condition of the rods is less than ideal."	Need to define "ideal."
p.5	S1G1-11 and S2A6-12 were chosen.	Explain why S2H6-12 and other segments from the top ends were not examined or evaluated.
p.6	III. Microstructure " banded nature of the microstructure is an indication that the material is not homogenous." "There was a relatively high amount of non-metallic stringer inclusions."	This is not unusual for commercial steel. This is also common in a commercial grade. Neither one is a specified requirement.

p.7	B. Rockwell C Hardness " … or was improperly heat treated."	Need validation lab work.
p.8	VI Charpy V-Notch Impact Test "When compared to requirements in other fastener material specifications such as ASTM A320[3] and ISO 898-1[4],"	This is irrelevant. ASTM A320 is for low temperature applications with strength requirements lower than those for ASTM A354 Gr BD.
p.9	Table 3 The chemical compositions by Anamet as well as by Gerdau do not show Sn, Sb, As, N, Bi, Pb contents. Discussion "EHE is caused by hydrogen introduced into the metal from external sources while it is under stress."	For failure analyses chemical compositions, all residual elements that can be detected should be reported. Gerdau reported 0.019Sn for the 2008 anchor rods and 0.009Sn for the 2010 anchor rods. Anamet analyses should have checked these out. "under stress" is an unnecessary condition for hydrogen diffusion, although stress will promote it.
p.11	"Lower hardness steel specimens, in the range of 25 – 38 HRC are not embrittled by the galvanizing process."	The failed anchor rod had 36 HRC near the surface, which contradicts the text.
p.12	Conclusions 1. "The root cause is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement."	What is normal susceptibility? The failed anchor rod samples only had 36 HRC at the surface.
	Table 1 A hardness variation from 29.3 to 38 HRC over a 0.010 inch distance is unusual for a surface layer.	Should have provided micrographs to account for the hardness variation.
	Anamet Report No. 5004.8612 Page 2, Figure 1 Some of the HRC indentations are within streaks caused by surface grinding, which may have lowered the hardness. See Photo at right.	 HRC traverse tests may have to be redone on a properly prepared surface.

3.2 Comments on Significant Technical Issues

3.2.1 Conclusions 1, 2, and 3

Conclusions 1, 2, and 3 of the report by Brahimi et al is reproduced below.

1. The anchor rods failed as a result of hydrogen embrittlement, 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.

2. The steel rods comply with the basic mechanical and chemical requirements of ASTM A354 grade BD.

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.

Conclusion 4 of the report is merely an announcement that supplemental requirements for replacement anchor rods are under review and needs no discussion here.

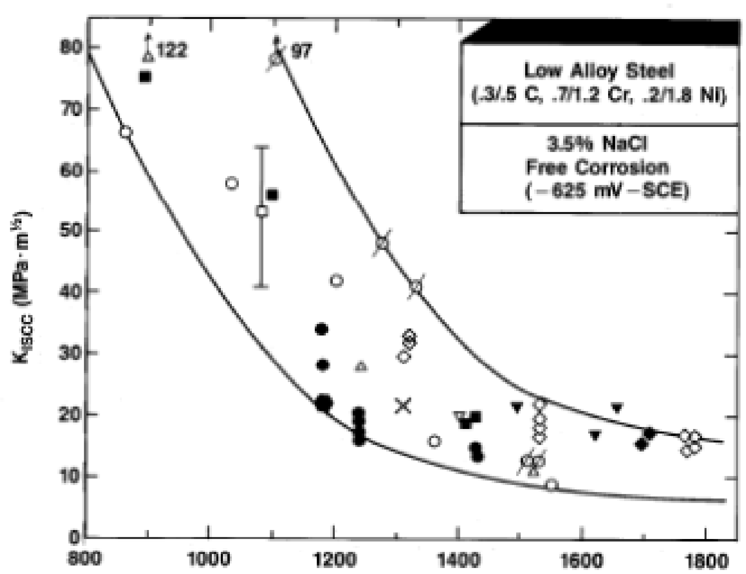


Figure 2 Relationship between K_{ISCC} (or KI_{HE}) and yield strength for low alloy steel. (Gangloff 1986)

As mentioned before, Conclusion 1 may not stand on its own merits without first defining what the normal susceptibility of a steel is. There is no known methodology that can be utilized to rate the susceptibility of a steel to HE for a given strength/hardness level. Most literature on hydrogen embrittlement and stress corrosion cracking of low alloy high strength steels indicate that KI_{HE} or K_{ISCC} (stress intensity for hydrogen embrittlement or stress corrosion cracking) is dependent on their strength/hardness levels (Figure 2).[14,15] For example, low alloy steels (e.g., 4140, 8640, and 4340) would have about the same susceptibility to HE for a given strength/hardness level.

[14] R. P. Gangloff: Hydrogen Assisted Cracking of High Strength Alloys, Figure 18, p.51.

[15] 1000 MPa ≈145 ksi; 40 MPa√m≈36.4 ksi√in.

"Low toughness and marginal ductility" are not main factors that would affect the HE susceptibility of an alloy. Aermet 100 is an ultrahigh-strength steel with high toughness. Thomas et al stated, "Near-peak-aged AERMET 100 is susceptible to severe internal hydrogen embrittlement (IHE) at 23ºC, if a sufficient diffusible hydrogen content is present, compromising the high toughness of this ultrahigh-strength steel."[16] If toughness and ductility in terms of elongation values in tensile tests are important factors that would affect the HE susceptibility, the authors need to provide laboratory data, technical references, or both to back up their conclusion. Eliaz et al stated, "a great variety of metallurgical parameters can influence the susceptibility of a structural steel to hydrogen."[17] Toughness, temper embrittlement, and nonmetallic inclusions are among a cloud of many minor metallurgical factors that would affect HE susceptibility.

In this regard, one of the important findings by Brahimi et al is that the failed anchor rods had 36 - 37 HRC near the surface, well below the 39 HRC maximum required for Gr BD. This would have a significant implication on the disposition of the 2010 anchor rods as well as the "supplemental requirements" for new anchor rods on order. To provide more hardness data from failed anchor samples, the authors should have evaluated the third anchor rod sample, S2H6. This sample was available; but the authors chose to do no laboratory evaluation on this.

Also, the microstructure being inhomogeneous may not be a factor in these failures. This is because the mass effects of the 3 inch diameter 4140 steel bar would produce microstructures that would vary from the surface to the core. This is to be expected and "normal" for the grade of steel, 4140, in sizes around 3 inches in diameter or larger. Whether the area ratio of "zone of incomplete transformation" in Photos 25 and 26 of the report seem higher than "normal" should have been verified by checking the microstructure of a sample (3" dia x 12 inches long) after subjecting it to the same heat treatment (1600^{o}F oil quenching, followed by 1025^{o}F tempering) as that indicated in the TC Industry's test reports.

3.2.2 Upquenching Effect as a Source of Hydrogen in the Anchor Rods

The authors of the report concluded that the anchor rods failed due to HE because "hydrogen was already present and available in the rod material as they were tensioned." This would be obviously true for any HE failures. They discussed two sources of hydrogen: (a) "The principal source of internal hydrogen was likely the freeing of trapped residual hydrogen by the upquenching effect of hot dip galvanizing" and (b) "galvanic corrosion of the sacrificial zinc coating generates hydrogen which is then absorbed by the cathode (i.e., steel)." They did not say, however, which one of the two was more responsible for the hydrogen in the S1 and S2 anchor rods when they were pretensioned in early March 2013.

As for the zinc coating corrosion, the authors did no laboratory work except for a visual evaluation of the failure regions. As for the "upquenching effect" for the hydrogen, the authored presented no convincing data or technical support. A 2009 paper by Brahimi was referenced as a technical support for the "upquenching effect" during hot dip galvanizing.[18] This "upaquenching

[16] Richard L.S. Thomas, et al: Internal Hydrogen Embrittlement of Ultrahigh-Strength AERMET 100 Steel, Metallurgical Transactions A, v.14A, February 2003, pp. 327 – 344.
[17] N. Eliaz, et al: Characteristics of Hydrogen Embrittlement, Stress Corrosion Cracking and Temper Embrittlement in High-Strength Steels, Engineering Failure Analysis, 9 (2002), pp. 167-184.
[18] S. Brahimi et al: Effect of Surface Processing Variables on Hydrogen Embrittlement of Steel Fasteners, Part 1: Hot Dip Galvanizing, Canadian Metallurgical Quarterly, 2009, 48(3), pp. 293-302.

effect" is in line with Townsend, who stated as follows regarding the hydrogen responsible for HE failures of high strength steel in his 1975 paper.[19]

> With regard to embrittlement due to internal hydrogen, the application of hot-dip zinc coatings is harmful. This effect is attributed to internal hydrogen which is released from trap sites during hot-dip coating and prevented from escaping from the steel by [Zn-Fe] intermetallic compounds which form at the steel surface.

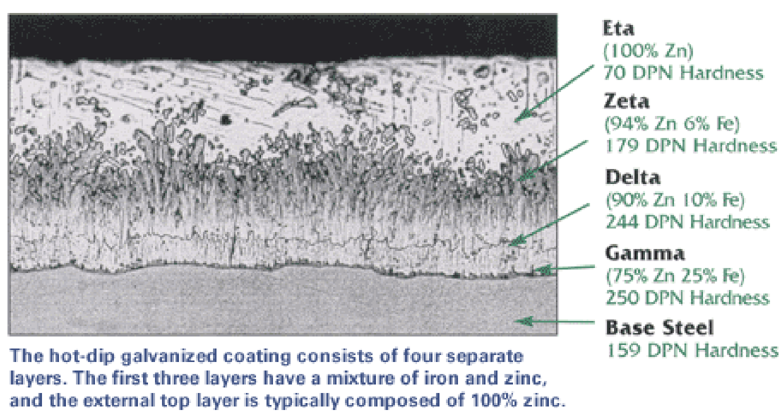
The trap sites would comprise dislocations, precipitates, undissolved metal carbides, martensite lath interfaces, etc. Whether the upquenching effect was mainly responsible for releasing the hydrogen that caused the HE failures of 32 anchor rods or not is open to question. The results obtained by Brahimi et al using small specimens may not be applicable directly to large anchor rods, which were immersed in a molten zinc bath for only a short time, probably about 4 or 5 minutes. The thermal response in these large anchor rods, some weighing as much as 400 pounds, during this short period would be substantially different from that in small specimens, each weighing about 0.12 pound. Without more research data on the mass effect of large anchor rods on the "upquenching effect," it would be premature to conclude that the hydrogen due to the "upquenching effect" during hot dip galvanizing had a significant role in the Pier E2 anchor rod failures.

One of the main objectives of this report would have to include some laboratory work that attempted to evaluate the environmental effects on the 32 anchor rod failures. As a minimum, the laboratory work should have included micrographs of the zinc coating in the fracture zone as compared with the top end of the same anchor rods. Also, some deposits/corrosion products on the zinc coating near the fracture face should have been analyzed, at least by energy dispersive spectroscopy (EDS). The authors did none of these except stating that "there was no significant visible corrosion on the broken rods (white corrosion or red rust…" Photo 5 shows the fracture face of S2A6. It had white deposits on the threads near the fracture face. No attempts were made to determine the nature of these deposits.

More importantly, the authors made no evaluation of the zinc coating thickness, not even for conformation of the report by the galvanizer.

Figure 3 is a micrograph that shows a typical zinc coating that forms on steel during hot dip galvanizing.[20]

The outer layer, the eta phase, of the zinc coating consists of almost pure zinc. This layer will be the first one to corrode when exposed to wetness.



The hot-dip galvanized coating consists of four separate layers. The first three layers have a mixture of iron and zinc, and the external top layer is typically composed of 100% zinc.

Figure 3 Micrograph of typical zinc coating from hot dip galvanizing

The authors should have evaluated the zinc coating in the

[19] H. E. Townsend: Effects of Zinc Coatings on Stress Corrosion Cracking and Hydrogen Embrittlement of Low Alloy Steel, Metallurgical Transaction, v. 6A, April 1975, pp. 877 – 883.
[20] http://www.galvanizeit.org/about-hot-dip-galvanizing/what-is-hot-dip-galvanizing/the-hdg-coating

fracture zone and compared it against the top end. It is possible that the zinc coating evaluation could have revealed some evidence of corrosion in the bottom end, which may be linked to the environmental hydrogen. The profile of the eta phase could have told if the coating experienced corrosion or not during the five years the S1 and S2 anchor rods stood idle in anchor rod ducts in Pier E2.

The "hydrogen uptake" from corrosion of zinc, steel, or both can be more significant than the "internal hydrogen" according to experts. Gangloff stated, "The probability that the Zn coating contained defects which permit the moist environment to contact the underlying steel would, of course, be an important issue." Other experts on HE failures of high strength steels said the following:

(a) "Another factor to consider is that the Zn gives anodic protection, forcing any exposed steel to act as a cathode. If only a bit of steel is exposed, the anode/cathode area ratio would be very high, meaning a high current density at the cathodic spots. It seems to me that this is a recipe for HIC, given the high hardness and plentiful presence of embrittling elements."

(b) "The main point that must not be overlooked is that corrosion hydrogen is a much bigger problem than process hydrogen in the embrittlement of steels..."

(c) "As the strength level increase, the amount allowable diffusible hydrogen content decrease, sometimes to the level of uncertainty in the practice of diffusible hydrogen measurements. At these lower hydrogen levels, the hydrogen distribution is as important as the average diffusible hydrogen."

(d) "The hydrogen from process or corrosion is likely to be higher in concentration near the steel surface than the core."

(e) "Controlling factors of fracture are local stress and local hydrogen concentrations."

Therefore, the source of hydrogen and its effects are a complex issue. The condition of the zinc coating of the anchor rod samples is an important issue that needs to be investigated further because the findings could affect the dispositions of the 2010 anchor rods for long term applications.

4.0 CONCLUSIONS

A review of the metallurgical failure analysis report by Brahimi et al on the failed S1 and S2 anchor rods in Pier E2 gave the following results.

(1) The report contains several simple errors, technical as well as editorial.

(2) The authors overlooked several important aspects of the anchor rod failures. Most importantly, they made no evaluation of the zinc coating in the fracture zone and the top ends.

(3) Some laboratory data including the Anamet's data need to be validated.

5.0 RECOMMENDATIONS

Allow a third party to conduct an independent metallurgical evaluation of all the anchor rod samples removed from Pier E2. The objectives are:

(a) Clarify what caused the 32 failures or clarify the environmental effects by evaluating the zinc coating and deposits in and around the fracture faces.

(b) Verify the hardness data that showed 36 HRC near the surface of the failed anchor rod samples.

(c) Request a complete chemical analysis from Anamet's emission spectrographic data, including the concentrations of all residual elements such as Sn, As, Bi, Zn, Ca, N, Pb.

(d) Conduct a heat treatment experiment to verify if the mixed microstructure at the core of the anchor rod samples resulted from improper hardening operation.