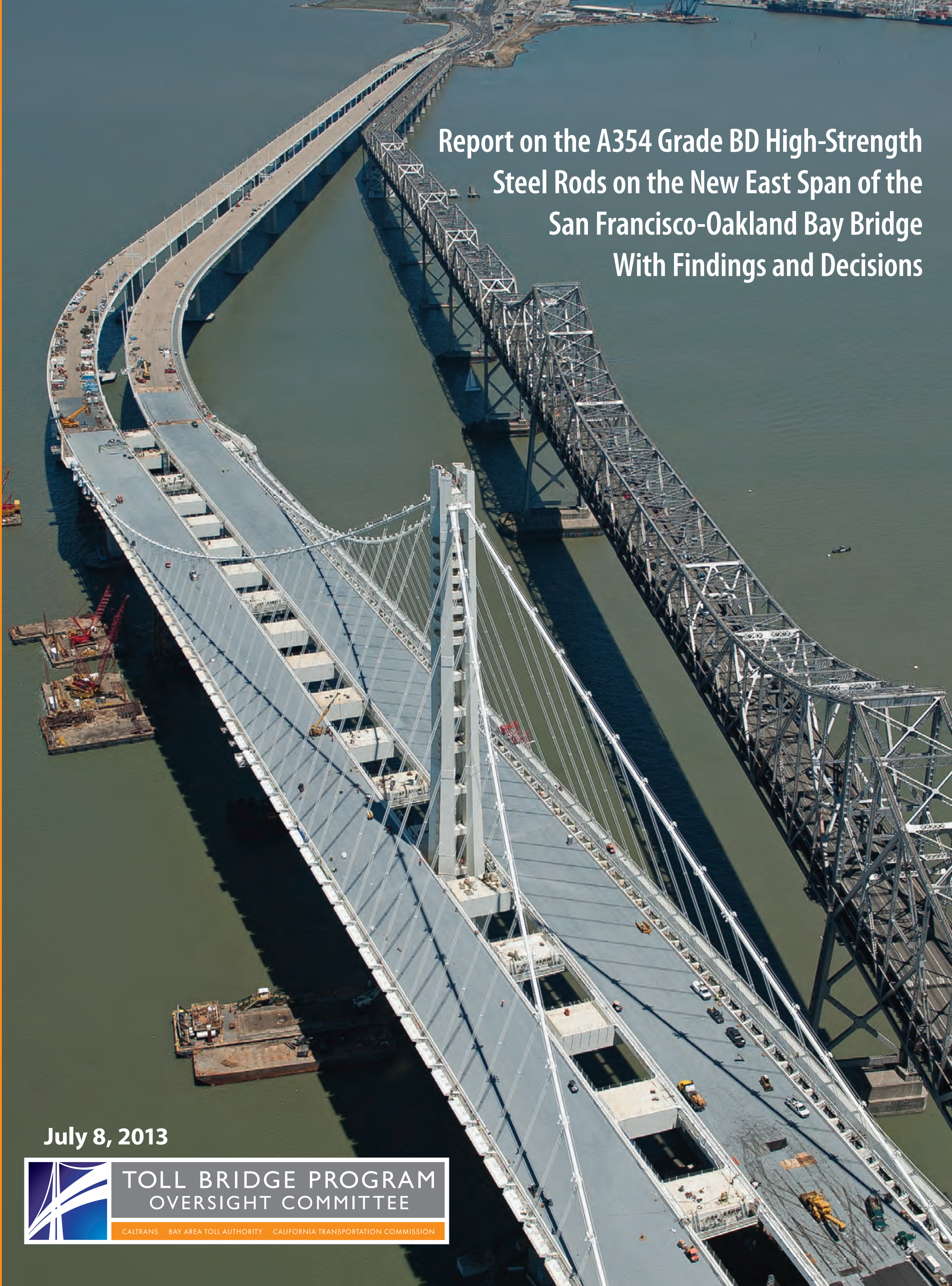


Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge With Findings and Decisions

July 8, 2013

TOLL BRIDGE PROGRAM
OVERSIGHT COMMITTEE

CALTRANS   BAY AREA TOLL AUTHORITY   CALIFORNIA TRANSPORTATION COMMISSION

TOLL BRIDGE PROGRAM
OVERSIGHT COMMITTEE

CALTRANS BAY AREA TOLL AUTHORITY CALIFORNIA TRANSPORTATION COMMISSION

On July 18, 2005, Governor Schwarzenegger and the State Legislature, through Assembly Bill 144 (AB 144), created the Toll Bridge Program Oversight Committee (TBPOC) to provide project oversight and project control for the Bay Area's Toll Bridge Seismic Retrofit Program, which includes the San Francisco-Oakland Bay Bridge East Span Replacement Project.

The TBPOC is composed of the Executive Director of the California Transportation Commission (CTC), the Director of the Department of Transportation (Caltrans), and the Executive Director of the Bay Area Toll Authority (BATA). The TBPOC's project oversight and control activities include: (a) reviews of contract bid documents and specifications, ongoing capital costs, significant change orders and claims; (b) implementation of a risk management program; and (c) resolution of project issues.

Current members are:

Steve Heminger, *Chair*
Executive Director, Bay Area Toll Authority

Malcolm Dougherty
Director, California Department of Transportation

Andre Boutros
Executive Director, California Transportation Commission

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

TOLL BRIDGE PROGRAM
OVERSIGHT COMMITTEE

CALTRANS BAY AREA TOLL AUTHORITY CALIFORNIA TRANSPORTATION COMMISSION

July 8, 2013

Department of Transportation
Office of the Director
1120 N Street
P.O. Box 942873
Sacramento, CA
94273-0001

web baybridgeinfo.org

Table of Contents

(continued on next page)

Table of Contents (continued)

List of Figures

(continued on next page)

List of Figures (continued)

List of Tables

Executive Summary

The Toll Bridge Program Oversight Committee (TBPOC) — composed of the executive directors of the California Transportation Commission, Caltrans, and the Bay Area Toll Authority — is charged with project oversight and control of the Bay Area's Toll Bridge Seismic Retrofit Program, which includes the new East Span of the San Francisco-Oakland Bay Bridge. As part of this charge, the TBPOC is investigating and resolving the challenge of the fractured A354 grade BD high-strength steel rods installed on the Self-Anchored Suspension (SAS) Bridge of the new East Span. When 32 of the 96 A354 grade BD high-strength anchor rods on shear keys S1 and S2 on Pier E2 failed in March 2013 after being tightened to their specified tension levels, the TBPOC launched an investigation into why these rods failed and whether the 2,210 other rods on the SAS Bridge also are at risk. The TBPOC directed its staff to investigate and report on what led to the failure of the 32 rods, what course of action is needed to address all the rods, and what implications the analysis, findings and recommendations from the investigation have on the TBPOC's determination of the timing for opening the new East Span to traffic.

As part of the investigative process, the TBPOC has gathered and analyzed available project records pertaining to the design, specifications, fabrication and construction activities related to the A354 grade BD rods on the SAS Bridge, and synthesized the technical analysis into this report. Specifically, the TBPOC did the following:

- Conducted four workshops on April 17, May 1, May 15, and June 25, 2013;
- Met over 25 times in person or by phone;
- Consulted with industry experts, the Seismic Peer Review Panel, and the Federal Highway Administration Review Panel;
- Reviewed over 50 documents and over 5,000 pages of material;
- Briefed the Bay Area Toll Authority (BATA) and the BATA Oversight Committee on March 27, April 10, April 24, May 8, and May 29, 2013;
- Presented and responded to questions during the California Senate Transportation and Housing Committee hearing on May 14, 2013; and
- Briefed members of the Bay Area State Legislative Delegation on June 6, 2013.

Three Investigation Questions

The TBPOC prepared this report in order to determine whether the issues pertaining to the A354 grade BD rods on the SAS Bridge have been satisfactorily addressed and, more importantly, to enable us to reach an informed decision on when the new East Span can open to traffic. The three key questions for this investigative report are:

1. What led to the failure of the A354 grade BD high-strength steel rods on shear keys S1 and S2, which were manufactured in 2008, on Pier E2 of the SAS Bridge?;

2. What retrofit strategy should be used to replace the lost clamping force of the rods?; and
3. What should be done about the other 2,210 A354 grade BD high-strength rods used elsewhere on the SAS Bridge?

A354 Grade BD Rods on the SAS Bridge

The SAS Bridge of the new East Span contains a total of 17 different types of A354 grade BD rods at seven different locations, for a total of 2,306 rods. Table ES-1 summarizes the location, description and quantity of rods used for each of the 17 rod types, and Figure ES-1 shows the locations where these rods are used on the SAS Bridge.

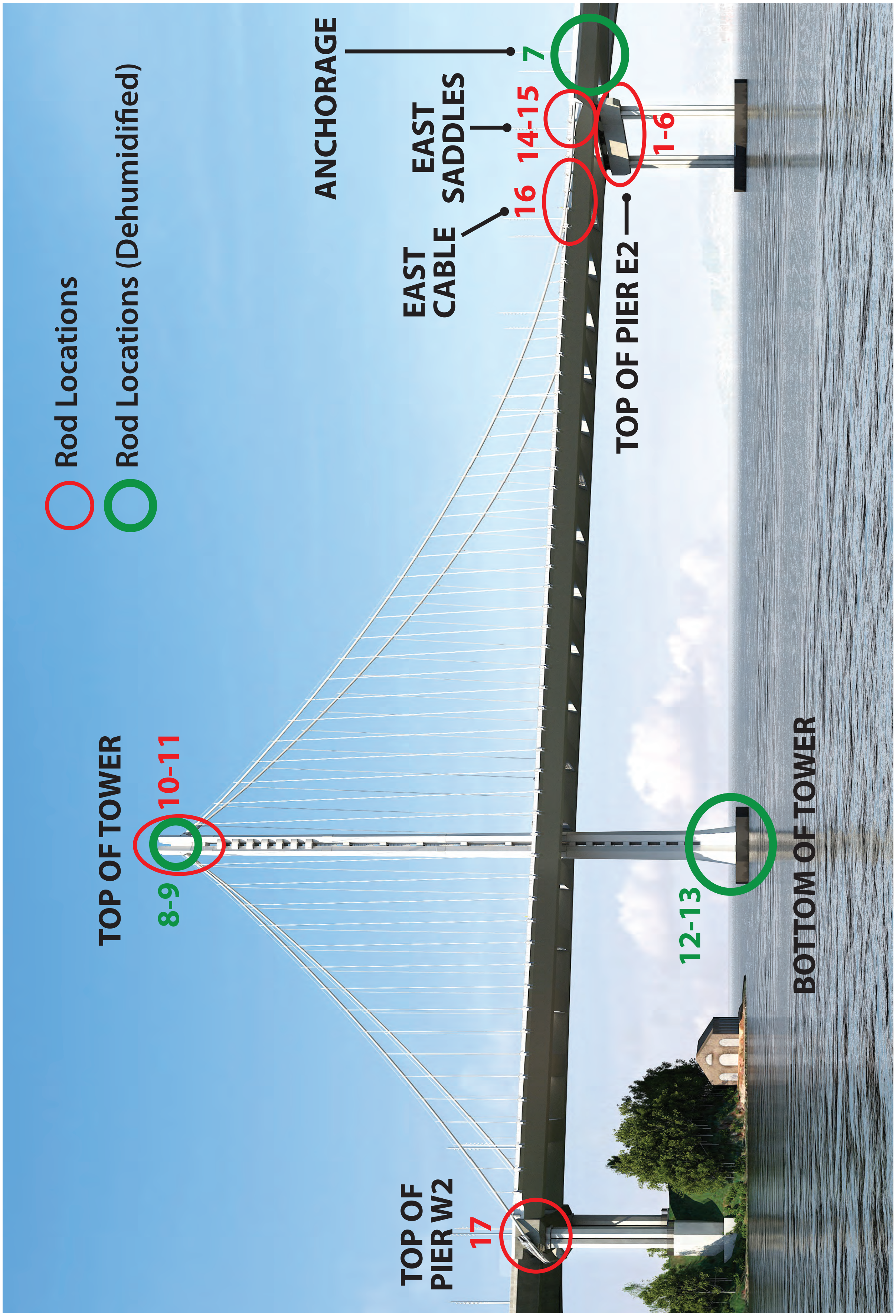
Of the total 2,306 rods, 288 3-inch diameter A354 grade BD high-strength steel rods are located in Pier E2 (48 rods at each of the four shear keys and 24 rods at each of the four bearings – see Items #1 and #2 in Table ES-1). These 288 high-strength steel rods connect the shear keys and bearings to the top of the E2 pier cap. In addition, there are 544 rods connecting the shear keys and bearings to the orthotropic box girders (OBG's) above them — see Items #3 and #4 in Table ES-1. As noted in Table ES-1, these rods are at the highest tension levels on the SAS Bridge.

Table ES-1 A354 Grade BD Rods on the SAS Bridge

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

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

Figure ES-1 A354 grade BD rod locations on the SAS Bridge



Question 1: What Led to the Failure of the A354 Grade BD Steel Rods on Shear Keys S1 and S2 at Pier E2?

Ninety-six (96) high-strength steel rods are installed on the lower housing of shear keys S1 and S2 (Item #1 in Table ES-1) at Pier E2. These rods were fabricated by Dyson Corporation in Ohio between June 4, 2008 and September 6, 2008 and installed by American Bridge/Fluor Joint Venture, the bridge contractor for the SAS Bridge, in October 2008. Figure ES-2 illustrates Pier E2 and the location of the shear keys, bearings, and their high-strength steel rods. Figure ES-3 shows the location of the fractured rods.

Figure ES-2 Bearings (B1-B4) and Shear Keys (S1-S4) in Pier E2

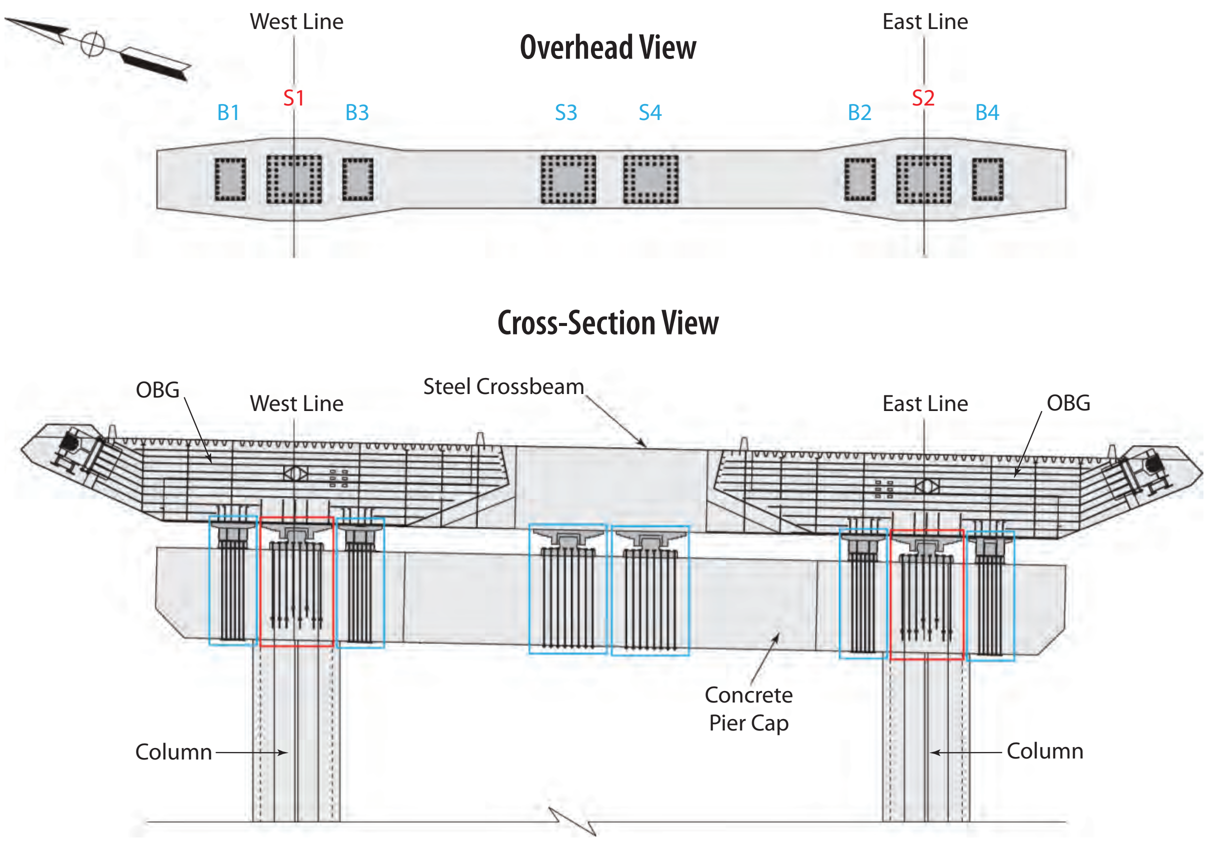
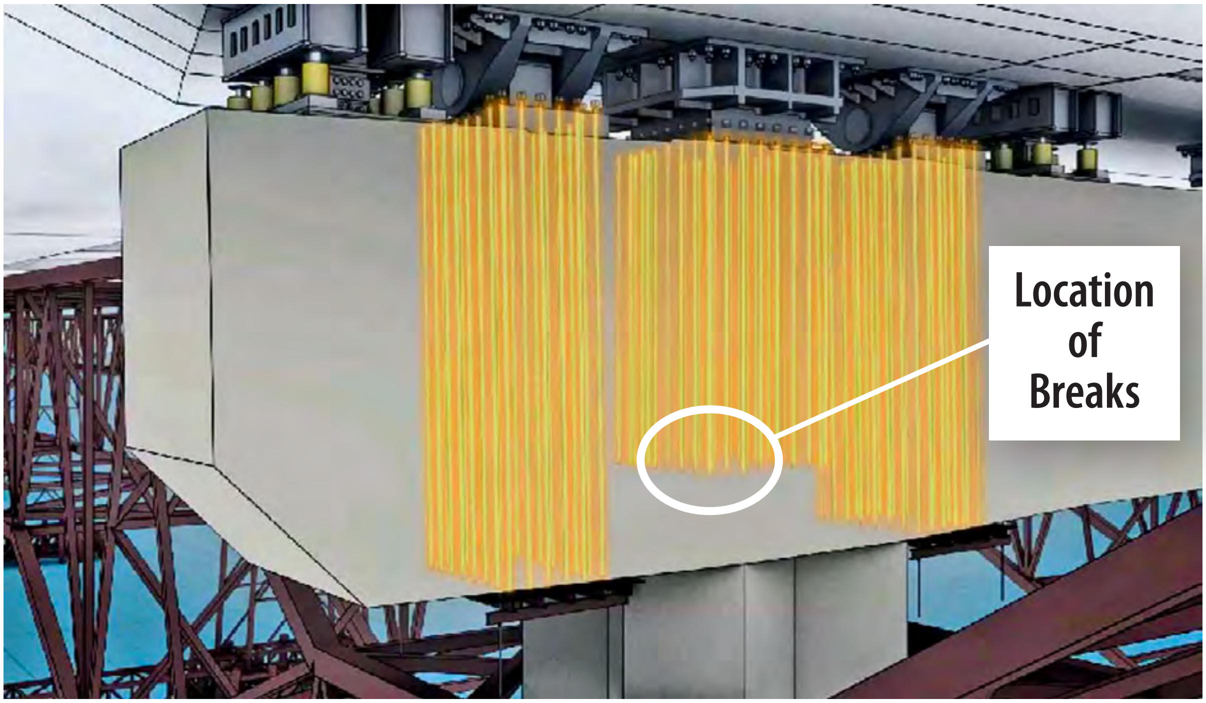


Figure ES-3: Location of Failed A354 Grade BD Anchor Rods



On March 1, 2013, following load transfer of the weight of the OBG roadway decks from the temporary falsework onto the main cable, American Bridge/Fluor Joint Venture tensioned the anchor rods at shear key S2. Between March 2 and March 5, 2013, American Bridge/Fluor Joint Venture tensioned the anchor rods at shear key S1. In accordance with contract plans and submittals, the rods were initially jacked to 0.75 Fu (i.e., 75 percent of their specified minimum ultimate tensile strength). Due to seating losses as the load is transferred from the hydraulic jack to the nut, the load then settled to its final design load of 0.68 Fu.

Between March 8, 2013 and March 14, 2013, 32 out of the 96 rods were discovered to have fractured. By March 14, 2013, Caltrans decided to lower the tension of the remaining unbroken rods from the 0.68 Fu to 0.45 Fu to avoid further fractures and to allow for investigation of the cause of the failures. The tension level was reduced on all unbroken rods. If the tension had not been reduced, it is possible that more of these 2008 high-strength steel rods at shear keys S1 and S2 would have fractured.

A metallurgical investigative team, composed of a consultant to American Bridge/Fluor Joint Venture (Salim Brahimi), a Caltrans metallurgist (Rosme Aguilar), and a consultant to Caltrans who is also principal/founder of Christensen Materials Engineering (Conrad Christensen), was tasked with examining the cause of the failures of the 2008 high-strength steel rods (Item #1 in Table ES-1).

Based on its examination of two of the extracted high-strength steel rods, the metallurgical investigation team on April 23, 2013, found that the rods failed due to hydrogen embrittlement, which is the process by which metals become brittle and fracture following exposure to hydrogen. The team concluded the following:

1. *The anchor rods failed as a result of hydrogen embrittlement (HE), resulting from the applied tensile load and from hydrogen that was already present and available in the rod material as they were tensioned. The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement.*

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

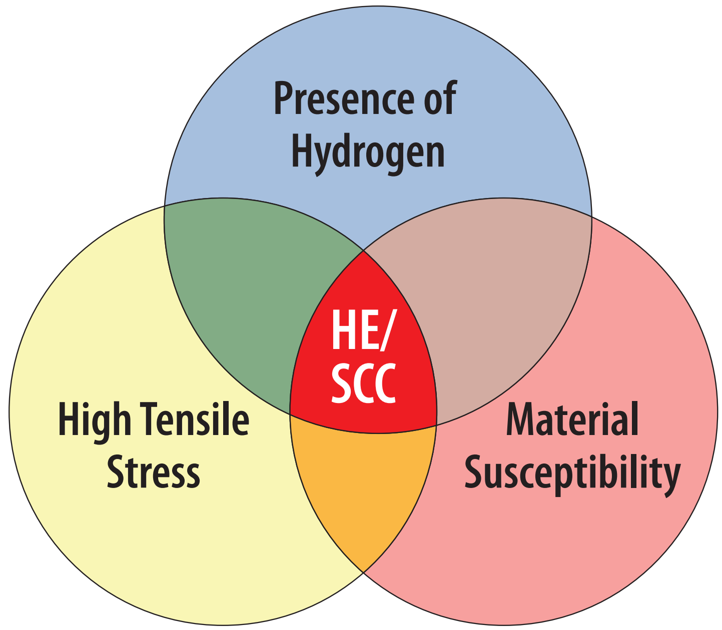
3. *The metallurgical condition of the steel was found to be less than ideal. More precisely, the microstructure of the steel is inhomogeneous resulting in large difference in hardness from center to edge, and high local hardness near the surface. As an additional consequence of the metallurgical condition,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

4. *Procurement of future A354 grade BD anchor rods should include a number of standard supplemental requirements to assure against HE failure. The appropriate specification of supplemental requirements is currently under review.*

Summary of the TBPOC Investigation

Hydrogen embrittlement is the root cause for the failure of the A354 grade BD high-strength steel anchor rods at shear keys S1 and S2 (Item #1 in Table ES-1). As used in this report, hydrogen embrittlement is considered a short-term phenomenon that occurs in metals, including high-strength steel, when three conditions apply: a susceptible material, presence of hydrogen and high tensile stress (as shown in Figure ES-4). To trace what led to the rod failures, this summary calls out each of the three hydrogen embrittlement conditions, and then tracks the events and decisions that either caused or contributed to that condition. In their totality, these events and decisions led to the failure of the 2008 A354 grade BD rods in March 2013.

Figure ES-4 Causes of Hydrogen Embrittlement (HE) or Stress Corrosion Cracking (SCC)



1. Material Susceptibility

Selection of A354 Grade BD Rods

The San Francisco-Oakland Bay Bridge was designated by Caltrans in October 1994 as an important "lifeline" structure because of its location along crucial transportation corridors. In short, this means that the Bay Bridge is to provide a high level of post-earthquake transportation service for emergency response and support for the safety and economic livelihood of the Bay Area. Combined with the West Span seismic retrofit, the retrofit of the west Yerba Buena Island viaduct and Yerba Buena Island tunnel, and the West Approach replacement, the replacement of the East Span would complete the lifeline connection across San Francisco Bay. Because of the Bay Bridge's designation as a lifeline structure, Caltrans required that the East Span Replacement Project incorporate design elements that exceed the requirements of standard seismic bridge design. The East Span Replacement Project was designed to withstand massive seismic accelerations expected only reoccur once every 1,500 years. The bridge's expected life span is 150 years, so there is approximately a 10 percent chance that such an earthquake would happen during its life span.

T.Y. Lin International/Moffatt & Nichol Design Joint Venture, the Engineer of Record, required the use of high-strength pre-tensioned rods and slip critical connections at Pier E2 to forge a strong physical bond at high-load locations on the SAS Bridge, taking into account bridge type, seismic design requirements, specified design loads and site-specific requirements (such as geology and geotechnical conditions). They selected A354 grade BD rods for use on the SAS Bridge as indicated in the SAS Design Criteria, which were finalized on July 15, 2002. Beyond the design requirements for a high-strength material, the decision to use A354 grade BD steel rods was also due to sole-source restrictions that discouraged use of proprietary rods, unless it could be established that there were no alternatives. Alternative high-strength rods such as F1554 and A722 rods were available for consideration by bridge designers for use on the SAS Bridge but not pursued due to sole-source restrictions.

Hot-Dip Galvanization

High-strength steels over 150 ksi possess a metallurgical structure that can have an affinity for hydrogen. The A354 grade BD high-strength steel rods for the SAS Bridge were hot-dipped galvanized to protect the steel from corrosion (except for Item #6 in Table ES-1). Hot-dip galvanization could make the A354 grade BD rod material susceptible to hydrogen embrittlement because the process requires the use of heat in which the fabricated steel is dipped into a bath of molten zinc at approximately 850°F. Too much heat could cause the release of internal hydrogen and when encapsulated in the zinc coating increases the risk of hydrogen embrittlement.

Correspondence between Caltrans and the T.Y. Lin International/Moffatt & Nichol Design Joint Venture in 2003 indicates that both parties were aware of the challenges with hot-dip galvanizing the A354 grade BD rods and the potential for hydrogen embrittlement. To avoid the problem, the initial specifications for the SAS Bridge contracts required the rods to be mechanically galvanized — a method of galvanizing that would subject the rods to less heat and less potential for hydrogen embrittlement — versus hot-dip galvanizing. However, a bidder inquiry at the time of advertisement of the East Pier/Tower (E2/T1) Marine Foundation Contract noted an inability to mechanically galvanize the large 3-inch and 4-inch diameter tower anchor rods. After further investigation, the general conclusion among both T.Y. Lin International/ Moffatt & Nichol Design Joint Venture and Caltrans design staff was that the tower rods were too long and too heavy for the mechanical process.

In March 2003, SAS design staff learned that the Richmond-San Rafael Bridge Seismic Retrofit Project also included A354 grade BD rods that were galvanized for corrosion protection. The Richmond-San Rafael Bridge Seismic Retrofit Project had changed its requirement for mechanical galvanizing of A354 grade BD rods to hot-dip galvanizing (because of the size of the rods), with an explicit instruction to use dry blast cleaning in lieu of cleaning in a pickling solution prior to galvanizing. The rods on the Richmond-San Rafael Bridge project were installed, in many locations underwater, to a low-tension snug-tight fit, without any apparent problems. Based on Caltrans' experience on the Richmond-San Rafael Bridge, and by adding a requirement that certified test results be submitted for conformance to ASTM A143, the SAS Bridge design team and the Caltrans design oversight team appeared reassured that hot-dip galvanizing could be performed successfully while avoiding hydrogen embrittlement by requiring dry blast cleaning in lieu of pickling for the A354 grade BD high-strength rods. This led to the issuance of Addendum #3 to the E2/T1 Marine Foundation Contract in April 2003, which included these requirements.

There is little documented discussion regarding the variety of applications and far higher tension levels that would be placed on some of the high-strength rods on the SAS Bridge and potential alternative corrosion protection methods.

Design and Contract Specifications

The Caltrans Bridge Design Specifications call for all ferrous bridge materials on a reinforced concrete bridge within 1,000 feet of a marine environment to be protected by hot-dip galvanizing or an equivalent protective method. Further, Caltrans Standard Special Provisions direct that high-strength fastener assemblies and other bolts attached to structural steel with nuts and washers shall be zinc-coated. For the A354 grade BD steel rods on the SAS Bridge, the T.Y. Lin International/Moffatt & Nichol Design Joint Venture selected galvanization for long-term corrosion protection. This choice was supported by the Caltrans design oversight team. The specifics on how and why galvanization was selected compared to other methods were not documented.

Heat Treatment

The 2008 A354 grade BD rods used at Pier E2 were reported to have strength and hardness well above the minimum requirements of the specification. Also, when examined, the failed rods showed that the metallurgical structure was not uniform across the thickness of the rod and parts did not have the expected material properties. This indicates the steel production and heat treatment were not fully successful in achieving the desired uniform metallurgical structure and desired material properties. Further, Quality Assurance (QA) also noted that the 2008 rods were subjected to a second heat treatment, as the documentation for the first treatment could not be produced by the fabricator. It is not uncommon to perform a second heat treatment. However, in this case, given what is now known about the poor quality of the 2008 rod material, the second heat treatment may have further hardened and strengthened the material and contributed to the rods' susceptibility to hydrogen embrittlement.

2. High Tensile Stress

The failed A354 grade BD anchor rods (Top of Pier E2 – Item #1 in Table ES-1) were loaded to very high tension due to design requirements at the connections which, when combined with a susceptible metallurgical structure and low toughness, led to a high risk of failures through hydrogen embrittlement. Because the SAS Bridge project utilized specifications developed for galvanized A354 grade BD rods for the Richmond-San Rafael Bridge Seismic Retrofit Project that were only snug tight, these specifications did not fully take account the high tensile stresses and associated risk to be imposed on the Pier E2 anchor rods. The SAS Bridge specifications for the A354 grade BD rods did not limit the hardness and tensile strength nor did they require minimum toughness levels in the rod material.

3. Presence of Hydrogen

Hydrogen Present in Rod Material

The metallurgical assessment of the failed A354 grade BD anchor rods (Item #1 in Table ES-1) concluded that they failed as a result of hydrogen embrittlement, resulting from the applied tensile load and from hydrogen that already was present and available in the rod material as the rods were tensioned. The visual examinations found evidence that hydrogen-assisted cracks were present in the rods and propagated prior to failure. Furthermore, the presence and appearance of the cracks, and the delayed nature of the fractures, point to time-dependence of the failure mechanism, including hydrogen-assisted cracking. When the fracture surfaces were further examined, there were inter-granular fractures at, and near, the thread root. The rod material also was found to not be homogeneous, as evidenced by the presence of ferrite and pearlite in between layers of martensite. Additionally, while ASTM A354 grade BD specifies a maximum bulk hardness of Rockwell 39 HRC, the rods show large disparities in hardness from center to edge, indicating that the steel may not have had optimal through-thickness hardenability or that it was improperly heat treated. The rod material also lacked toughness, with low Charpy Impact values ranging from 13.5 to 17.7 ft-lb.

Embedded Rods in Pier E2 Exposed to Environment

The failed A354 grade BD anchor rods installed at Pier E2 were manufactured by Dyson in Ohio in 2008, and were installed prior to the final concrete pour on December 5, 2008. These high-strength steel rods were embedded within the pier directly above the columns, and were sitting in ducts for five years before they were tensioned. During this five-year period, water was pumped out of the ducts a number of times at the request of Caltrans. Temporary drainage and sealing arrangements had not prevented the ingress and collection of rainwater, since it had not been anticipated that there would be such an extended period prior to completing the erection and grouting operation at Pier E2. The actual length of time during which water was present in these holes is unknown, but the presence of water may have been a contributing source of hydrogen contamination in the rods.

Conclusion

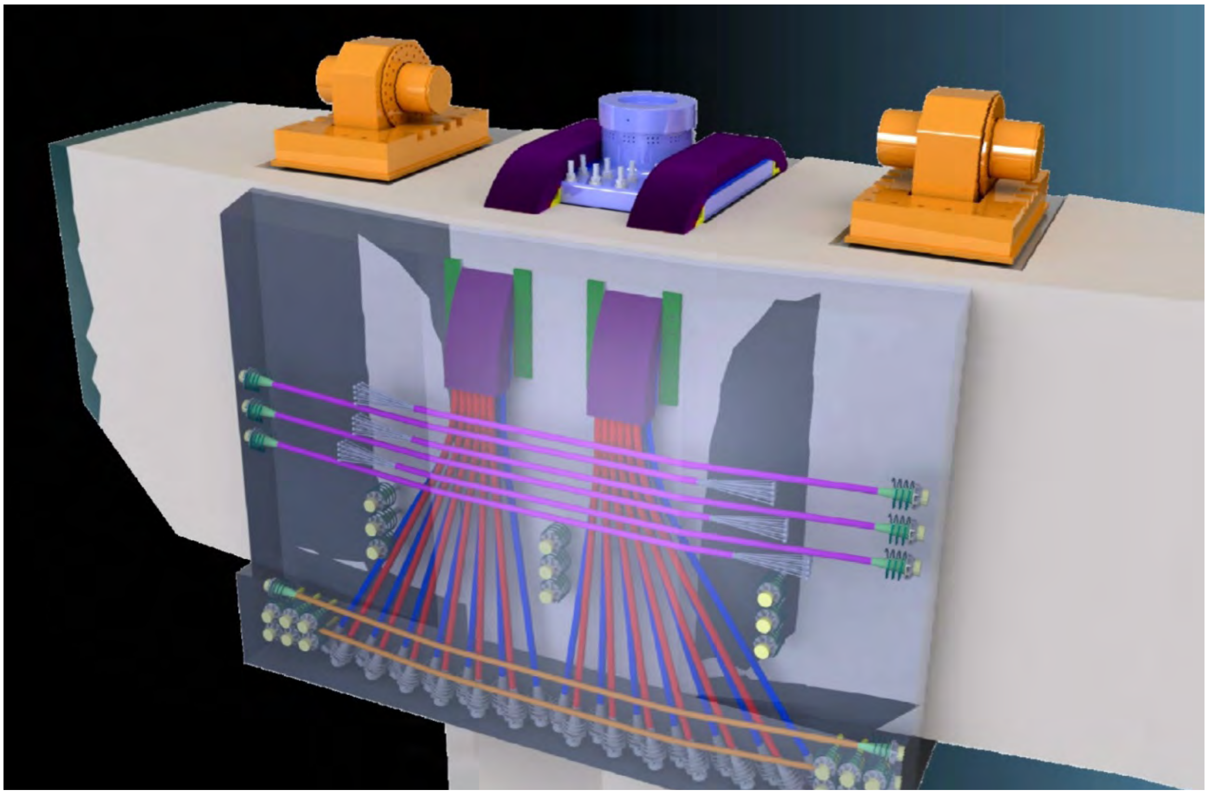
The A354 grade BD anchor rods installed on the lower housing of shear keys S1 and S2 failed due to hydrogen embrittlement. The three conditions of susceptible material, high tensile strength and the presence of hydrogen all were present, leading to crack extension and brittle fracture. The actions taken and decisions made on the design and specifications, fabrication, and construction activities are all contributing factors to the rod failures.

Question 2: What retrofit strategy should be used to replace the lost clamping force of the rods?

The 2008 A354 grade BD rods installed in Pier E2 cannot be replaced. These rods were installed and embedded into the Pier E2 cap and are in-line with the vertical columns of the pier. In addition, the OBGs have been placed over the shear keys, further limiting access to the rods. Therefore, replacing these 96 rods would require significant destruction of the pier cap to allow for the removal of the 2008 rods and installation of replacement rods. Thus, the lost clamping force from the failure of the 2008 rods must be replaced in another fashion.

After review of three retrofit design options, on May 8, 2013, the TBPOC unanimously approved selection of the steel saddle retrofit option after finding that it would meet all design requirements and objectives of the project. As shown in Figure ES-5, it also applies a direct preload to the lower housing via the radial forces that are developed from the main vertical post-tensioning force being applied as intended in the original design. The project's Seismic Peer Review Panel also supported this option, and the American Bridge/Fluor Joint Venture indicated this option would be the easiest to construct and the fastest option to complete.

Figure ES-5 Recent Rendering of Selected Steel Saddle Option



Question 3: What should be done about the other 2,210 A354 grade BD high-strength rods used elsewhere on the SAS Bridge?

No Further Rod Failures from Hydrogen Embrittlement

A monitored, time-dependent, *in-situ* tensioning test was conducted on all remaining 192 rods to determine their susceptibility to hydrogen embrittlement. This tensioning test was conducted over a period of 30 days, which was considered sufficient time to ascertain whether 'internal' hydrogen was likely to embrittle the rods. Tensioning of the 192 rods was completed on April 9, 2013, at which time the 30-day *in-situ* test period began. The 30-day *in-situ* test period was completed on May 9, 2013 and resulted in no rod failures or evidence of hydrogen embrittlement. As of July 1, 2013, these rods continued to perform as designed.

As for the remaining 2,018 A354 grade BD rods, none have failed, and all have been under tension from 91 to 1,429 days as of July 1, 2013. Because hydrogen embrittlement is a time-dependent phenomenon, also dependent on the level of sustained tension, these rods have low risk of hydrogen embrittlement. In contrast, approximately 30 percent of the anchor rods in shear keys S1 and S2 failed just 3 to 10 days after tensioning to their design loads, and more might have failed if that tension level had been maintained.

Longer-Term Risk of Stress Corrosion Cracking

Stress corrosion cracking is time-dependent — it occurs over years or decades of sustained tension and is based on the commencement and rate of corrosion. The longer-term concern is whether the remaining A354 grade BD rods are susceptible to stress corrosion cracking and, if so, when cracking may occur. Like hydrogen embrittlement, there are three factors that contribute to stress corrosion cracking — susceptible material, high tensile stress and hydrogen-related corrosion. Without any one of these three conditions, stress corrosion cracking will not occur.

Stress corrosion cracking develops in response to the tension the rod is placed under, its diameter, threads and the hardness of material. Individual rods with higher tension levels and hardness levels at or above 35 HRC should be further evaluated for risk to stress corrosion cracking.

Five tests — *in-situ* hardness test (Test I), Rockwell hardness test (Test II), Charpy V-Notch test for toughness and chemical composition (Test III), and two accelerated stress corrosion cracking tests (Townsend Test IV and Raymond Test V) — were designed to evaluate the risk of stress corrosion cracking. All tests, except for Tests IV and V, were completed by June 21, 2013. Tests II and III were conducted by independent laboratories in Texas and in Richmond, California. The results from Tests I, II and III verified the mechanical properties of the rods and categorized each rod by hardness.

Tests I, II and III for the other rods verified QC/QA test results and confirmed that the rods have low risk for near-term hydrogen embrittlement failures because the rods exhibit better metallurgical uniformity and improved toughness as compared to the failed 2008 rods. As noted earlier, these rods have performed successfully under tension from a minimum of three months to a maximum of nearly four years.

For the longer-term stress corrosion cracking, there are a number of rods that exhibit surface hardness that is in excess of 35 HRC, a point at which there is increased risk for stress corrosion cracking under sustained high tension. However, based on the tests, these rods also exhibit better metallurgical uniformity and improved toughness. Further, many of the remaining rods are not subject to high sustained tension levels or are located in dehumidified or sealed areas that provided additional corrosion protection. Further, stress corrosion testing is underway as part of Tests IV and V that will provide important data for further analysis and remediation of the rods.

Findings

Based on the information gathered and analysis in this investigative report, the TBPOC makes the following findings:

1. As noted in the joint Caltrans - American Bridge/Fluor Joint Venture metallurgical report dated May 7, 2013, "The [2008] 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." However, that same report concluded that "the steel rods comply with the basic mechanical and chemical requirements of ASTM A354 grade BD," which was the basis of the rod specification selected by the designer and owner of the project.
2. The three factors contributing to the risk of failure due to hydrogen embrittlement are the presence of hydrogen, high tensile loads and the susceptibility of the material to hydrogen. The contract specifications for the East Span did not consider the unique requirements of the seven different rod locations on the SAS Bridge. One specification was inappropriately applied to all locations. In addition, it was inappropriate to adapt the fastener specification modified during the Richmond-San Rafael Bridge Retrofit Project, where the A354 grade BD galvanized rods were deployed underwater at low tension (snug tight), to the E2/T1 Marine Foundation and SAS Superstructure contracts for the new east span, where similar bolts were deployed above water and at considerably higher tension levels.
3. There was inadequate consideration to allow for sole-source specifications, utilizing alternative or specific mechanical properties of steel. In fact, proprietary Macalloy high-strength rods were specified for the pre-stressing rods in the W2 cap beam in the SAS special provisions. Investigation into other types of high-strength steel rods, even if they might have required sole-sourcing, appears to have been warranted.
4. There was inadequate consideration given to the combined effect of high-strength rod material requirements and corrosion protection. The fastener selection process was completed during design, and the corrosion protection specification was modified dur-

ing advertisement and construction. There was no subsequent return discussion to the fastener selection decision.

5. There was inadequate consideration of alternative corrosion protection treatments, given well-known concerns about the risk of hydrogen embrittlement from hot-dipped galvanizing of A354 grade BD rods. In particular, alternative treatments such as Geomet®, or greased and sheathed, or painted solutions should have been more fully considered depending on the various sizes and applications. A life cycle cost analysis should have been prepared for the various rod alternatives and the various methods of long-life corrosion protection.
6. The fastener specification for the E2/T1 Marine Foundations and SAS Superstructure contracts relied too heavily on generic ASTM standards and should have included special provisions reflecting a better understanding of the principles of the ASTM standards to guard against hydrogen embrittlement. In particular, the contracts should have more clearly addressed the following four requirements: 1) maximum steel hardness and through consistency, 2) minimum steel toughness, 3) magnetic particle testing, and 4) a time-dependent test of the rods under tension prior to their installation on the new bridge. As one peer review panelist noted: "National Standards are the minimum. You still need to do good engineering."
7. The construction of Pier E2 should not have allowed for water to collect during the construction process. The collection of water in their support cylinders may have exacerbated the embrittlement of the 2008 high-strength steel rods. Because the rods were to be embedded in concrete, it was infeasible to remove and replace them. In the words of one engineer, "A good design should not be so sensitive to bad material."
8. ASTM 143 required a hydrogen embrittlement test. The designer was aware of the potential of hydrogen embrittlement, but construction oversight technicians only tested rods with 1½-inch diameter or less. The large-diameter rods were not tested for hydrogen embrittlement and a Request for Information was not issued. Closer coordination was needed between design and construction staff.
9. It took a considerable amount of time including significant manual effort to assemble the QC/QA information for the SAS rods. In the case of the E2/T1 Marine Foundation contract, much of the information has not been located for a contract completed as recently as 2008. Such information is vital not only for an investigation of materials failure such as this, but for routine maintenance and major rehabilitation of the SAS over its 150-year design life.

Responsible Parties

The design and construction of the Self-Anchored Suspension (SAS) Bridge of the new East Span involved several responsible parties:

- Caltrans is the owner and operator of the New East Span;
- T.Y. Lin International/Moffatt & Nichol Design Joint Venture is the Engineer of Record;

- American Bridge/Fluor Joint Venture is the contractor for the SAS Superstructure; and
- Kiewit/FCI/Manson Joint Venture is the contractor for the SAS E2/T1 Marine Foundation.

These parties are responsible for the actions that led to the following findings:

- T.Y. Lin International/Moffatt & Nichol Design Joint Venture, American Bridge/Fluor Joint Venture and Caltrans jointly share responsibility for Findings 1 and 7.
- T.Y. Lin International/Moffatt & Nichol Design Joint Venture and Caltrans jointly share responsibility for Findings 2, 3, 4, 5 and 6.
- American Bridge/Fluor Joint Venture and Caltrans jointly share responsibility for Finding 8.
- Caltrans is responsible for Finding 9.

TBPOC Decisions and Actions

Based on the findings above and review of the 17 locations where A354 grade BD are located on the East Span, there are four categories into which this report classifies the 2,210 high-strength steel rods on the SAS Bridge:

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

Table ES-2 depicts a provisional approach for remediating the stress corrosion cracking potential of the various A354 grade BD rods on the SAS Bridge. These recommendations are provisional pending completion of the final tests (referred to as the Townsend Test and Raymond Test). In no case, however, do we expect the remaining tests to indicate that any rods, other than the failed Item #1 anchor rods, will need to be replaced before opening the new East Span to traffic. The risk of near-term hydrogen embrittlement has passed. The potential for longer-term stress corrosion cracking can be managed safely and effectively after the SAS is placed into service.

Rod-by-Rod Resolution

Table ES-2: Recommended Rod-by-Rod Resolution

	Construction	Maintenance			
Location	Replace Before Opening	Replace After Opening	Reduce Tension	Augment Dehumidification	Accept and Monitor
E2	1. Shear Key Anchor Rods* (bottom) *replaced by steel saddle retrofit	2. Bearing & Shear Key Anchor Rods (bottom) 3. Shear Key Rods (top) 4. Bearing Rods (top)			5. Bearing Assembly (bushings) 6. Bearing Retainer Ring Plate Assembly
Anchorage				7. PWS Anchor Rods	
Top of Tower		11. Outrigger Boom	8. Saddle Tie Rods 9. Saddle Turned Rods		10. Saddle Grillage
Bottom of Tower			12. Tower Anchor Rods (Type 1) 13. Tower Anchor Rods (Type 2)		
East Saddle					14. East Saddle Anchor Rods 15. East Saddle Tie Rods
East Cable					16. Cable Band Anchor Rod
W2					17. Bikepath Anchor Rods

Note: Dehumidification is already in place for the Top of Tower, Bottom of Tower and Main Cable Anchorage.

The rod-by-rod resolution displayed in Table ES-2 details the remediation strategy for each grouping of A354 grade BD rods. The “Replacement Before Opening” is self-explanatory. “Replace After Opening” and “Augment Dehumidification” are anticipated to occur before the end of 2014 to take advantage of the efficiencies offered by the existing contractor and the temporary work platforms that are still in place. Rods confirmed by T.Y. Lin International/Moffatt & Nichol Design Joint Venture, the Engineer of Record, as being appropriate for reduction in tension will be adjusted as soon as the load distribution ceases to change due to construction activities. The rods labeled “Accept and Monitor” do not require remediation and illustrate the fact that the original specification used for all 17 rod locations was only appropriate for fasteners installed under low tension. All high-strength rods will require routine and periodic maintenance.

Revised Specifications for Replacement Rods

Additional high-strength steel rods are to be purchased to replace the 2010 rods on Pier E2 that have been selected for testing. The remediation strategy outlined above also will require procurement of additional high-strength steel rods. Caltrans has applied supplementary specifications for the rods identified for replacement, which limit the ultimate tensile strength, minimum toughness, maximum hardness and impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring homogeneous metallurgical structure. Caltrans also will be performing the time-dependent hydrogen embrittlement “pull test” required by ASTM F606 and the Townsend and Raymond Tests to determine the replacement rods’ susceptibility to stress corrosion cracking. Finally, alternative corrosion protection methods will be evaluated. The Toll Bridge Program Oversight Committee will review and approve all major actions regarding procurement of replacement rods.

Maintenance Plan

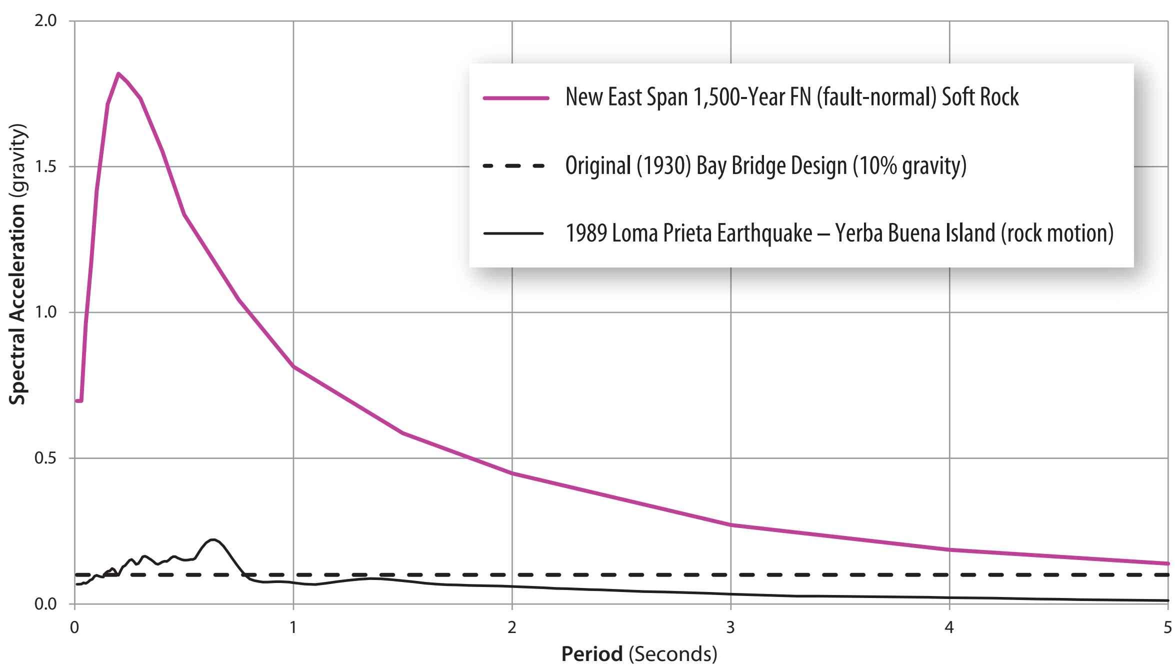
One of the tasks of the design team is to prepare Bridge Maintenance and Inspection Manuals for each of the major components of the East Span shown in Figure ES-1, as each component is completed. Each set of manuals will provide documentation on the design, documentation on the construction, load ratings, detailed inspection procedures for each major element, an initial “baseline” inspection and inventory, sources and reference material, and post-seismic inspection and repair procedures. The manuals are to be used primarily by personnel engaged by Caltrans to perform routine inspections, in-depth or special inspections, and routine maintenance on the East Span structures. Regarding the A354 grade BD rods, the maintenance plan for these elements of the SAS Bridge will include existing baseline information (test data, etc.), required monitoring and testing, inspection and testing methods to be employed, required intervals, required routine and periodic maintenance, protocols for notification and action when required, and actions required after an extreme event (earthquake, vessel collision, etc.).

Bridge Opening

The TBPOC concludes that it is safe to open the new East Span after replacing the capacity lost by the failed 2008 rods. It is unnecessary to replace any of the remaining rods (Items #2 through #17) before the bridge opening since the risk of near-term hydrogen embrittlement has passed, and especially in light of the safety imperative of moving traffic off the seismically deficient existing East Span Bridge. While some rods are highly susceptible to longer-term stress corrosion cracking, ample evidence exists than none are at high risk of near-term fracture.

Ground accelerations have been plotted in Figure ES-6 comparing the design of the new East Span with the 1936 East Span and recorded Loma Prieta earthquake accelerations in 1989. The Loma Prieta earthquake was a 6.9-magnitude earthquake centered nearly 60 miles away from the Bay Bridge that still caused the partial collapse of a section of the existing cantilever structure. While the west spans of the Bay Bridge have been fully retrofitted, the east span of the bridge is still vulnerable until replaced.

Figure ES-6 Comparison of Ground Accelerations



1. Report Purpose

This report provides factual information on all A354 grade BD high-strength steel rods installed on the Self-Anchored Suspension (SAS) Bridge of the new East Span of the San Francisco-Oakland Bay Bridge. These A354 grade BD rods are quenched and tempered alloy steel elements that have a minimum specified tensile strength of 140 kilopounds per square inch (ksi) and a specified Rockwell hardness of 31 to 39 HRC for rods over 2½ inches in diameter. They meet the mechanical and chemical requirements defined in American Society for Testing and Materials (ASTM) A354 grade BD. The report presents the technical analysis, findings, and conclusions on what led to the failure of a portion of the A354 grade BD rods on the east pier of the SAS Bridge, as well as recommendations for addressing these and other rods used on the SAS Bridge.

The analysis focuses on three questions:

1. What led to the failure of the A354 grade BD high-strength steel rods on shear keys S1 and S2, which were manufactured in 2008, on Pier E2 of the SAS Bridge?;
2. What retrofit strategy should be used to replace the lost clamping force of the rods?; and
3. What should be done about the other 2,210 A354 grade BD high-strength rods used elsewhere on the SAS Bridge?

Based upon the findings of the investigation, this report classifies the high-strength rods into four categories:

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

These rod-by-rod resolution recommendations are provisional pending completion of the final tests (referred to as the Townsend Test and Raymond Test).

Note that at the request of the Toll Bridge Program Oversight Committee (TBPOC), the Federal Highway Administration (FHWA) is conducting an independent review of the process and analysis supporting the conclusions reached in this report regarding questions 1 and 3 above. In addition, the project's independent Seismic Peer Review Panel has provided comments on the report, and will provide its written review to the TBPOC under separate cover.

2. Overview of San Francisco-Oakland Bay Bridge East Span Replacement Project

Why a New East Span?

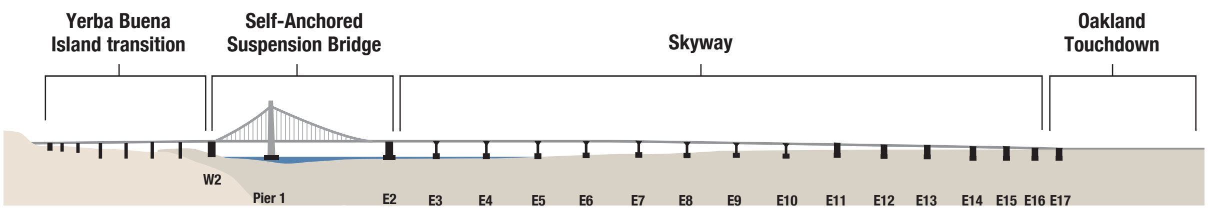
On October 17, 1989, the Loma Prieta earthquake caused a 50-foot, 250-ton section of the upper deck of the East Span of the San Francisco-Oakland Bay Bridge (Bay Bridge) to collapse onto the deck below. The earthquake reached a magnitude of 6.9 on the Richter scale — the largest earthquake the San Francisco Bay Area has experienced since the earthquake of 1906. The Loma Prieta earthquake left 63 people dead and 3,757 injured, and thousands of people were left homeless.

On January 29, 2002, construction began on the new East Span. The new East Span is 2.2 miles long on an alignment parallel to and north of the existing East Span. The original East Span will be demolished after the new East Span is opened to traffic. When completed, the new East Span will consist of four major sections (described in detail below), but will appear as a single unified structure. The new East Span will include two side-by-side bridge decks, each with five travel lanes and standard 10-feet-wide shoulders. Additionally, there will be a shared bicycle and pedestrian path located on the south side of the eastbound deck of the span.

Components of the East Span

The new East Span of the Bay Bridge consists of four major components: 1) the Yerba Buena Island Transition Structures; 2) the Self-Anchored Suspension (SAS) Bridge; 3) the Skyway; and 4) the Oakland Touchdown approach. Figure 1 depicts the four components of the new East Span.

Figure 1 Major Components of the East Span



The **Yerba Buena Island Transition Structures** connect the SAS Bridge to the Yerba Buena Island tunnel, and will transition the East Span's side-by-side traffic to the upper and lower decks of the tunnel and the West Span. The new structures are made of cast-in-place reinforced concrete, with 13 supports (footings and columns).

The **Skyway** is a 1.2-mile-long elevated viaduct between the SAS Bridge and the Oakland Touchdown, with two parallel roadways that will each accommodate five lanes of traffic in each direction and two 10-foot-wide shoulders to help keep vehicles moving during a traffic incident. The Skyway has large pilings driven deep into a dense material known as the Alameda formation, and contains seismic safety devices that will enable the road decks to slide, rather than buckle, in the event of an earthquake. The Skyway's decks are composed of 452 pre-cast concrete segments, each standing three stories high and measuring 90 feet wide and 25 feet long.

The **Oakland Touchdown** connects the Skyway structure to the Oakland shoreline. These approaches are a combination of cast-in-place reinforced concrete structures and light-weight fill roadways that provide a gradual transition from the new bridge to the toll plaza.

Self-Anchored Suspension (SAS) Bridge

The SAS Bridge, with its single 525-foot-tall steel tower, is 2,047 feet in length and like the other three East Span components is designed to withstand a massive earthquake. While traditional suspension bridges have twin cables connected to the roadway deck by smaller suspender cables, the SAS Bridge features a single continuous main cable that is anchored within the eastern end of the roadway, carried over the tower, wrapped around the two side-by-side decks at the western end, carried back over the tower, and then anchored again in the roadway at the eastern end.

Tower

The steel tower is made up of four separate steel legs connected by shear link beams, which are designed to act like fuses and absorb most of the shock during an earthquake and to protect the tower from significant damage. The damaged beams can then be individually removed and replaced.

Pier W2

The single main cable wraps around this pier, like a sling cradling a stone. Pier W2 holds down the cable and is supported by some of the largest foundation works ever constructed by Caltrans.

Pier E2

Pier E2 is the first pier east of the main tower of the SAS Bridge, near the point where the twin steel orthotropic box girder (OBG) roadways of the SAS meet the concrete decks of the Skyway. Within the OBGs at this end are the anchorages for the single main cable that carries the weight of the bridge. The OBGs are connected to the pier by bearings and protected from seismic movement by shear keys. There are a total of four shear keys (S1 through S4) and four bearings (B1 through B4) at the top of Pier E2.

The SAS Bridge, together with the shear keys, has been designed to withstand a 1,500-year seismic event. The shear keys at Pier E2 are intended to transfer the forces from the combined superstructure (SAS Bridge and Skyway Bridge) into Pier E2 during a seismic event, the forces being both in the East-West and North-South directions.

Shear keys S1 and S2 are located at the centerlines of the OBGs directly above the pier columns. Shear keys S3 and S4 are located on the concrete pier cap between the OBG sections and under the steel crossbeam.

The four bearings, B1 through B4, are designed to perform the normal duty of providing fixity and accommodating thermal expansion of the OBGs during everyday use. In the event the shear keys fail during a major seismic event, the bearings also serve as a back-up system to transmit the seismic load.

A354 Grade BD Rods on SAS Bridge

The SAS Bridge of the new East Span contains a total of 17 different types of A354 grade BD rods at seven different locations, for a total of 2,306 rods. These rods range in diameter from 1 inch to 4 inches. Table 1 summarizes the location, description and quantity of rods used for each of the 17 rod types, and Figure 2 shows the locations where these rods are used on the SAS Bridge.

Of the total 2,306 rods, 288 3-inch diameter A354 grade BD high-strength steel rods are located in Pier E2 (48 rods at each of the four shear keys and 24 rods at each of the four bearings — see Items #1 and #2 in Table 1). These 288 high-strength steel rods connect the shear keys and bearings to the top of the E2 pier cap. In addition, there are 544 rods connecting the shear keys and bearings to the OBGs above them — see Items #3 and #4 in Table 1. As noted in Table 1, these rods are at the highest tension levels on the SAS Bridge.

Table 1 A354 Grade BD Rods on the SAS Bridge

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

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

Figure 2 A354 Grade BD Rod Locations on the SAS Bridge

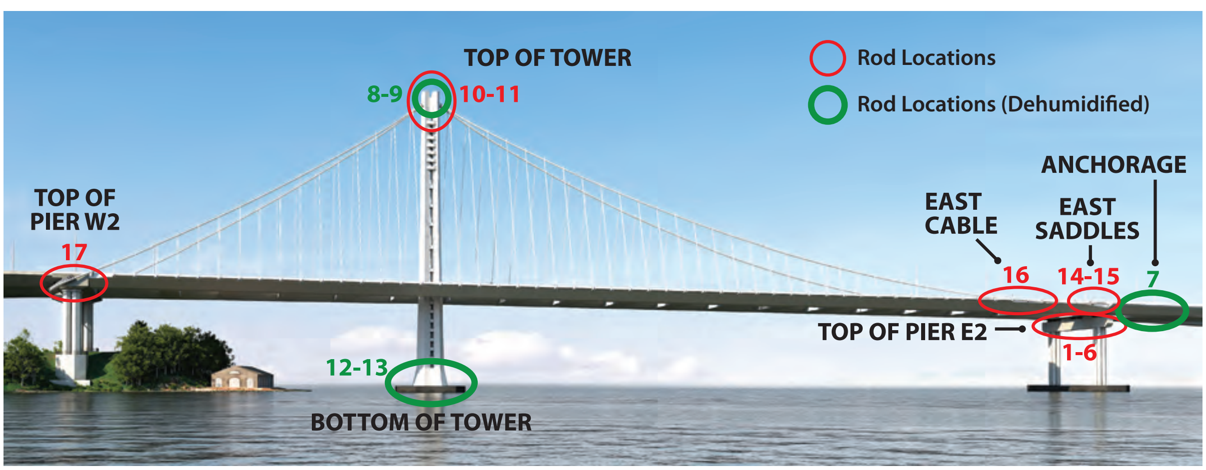
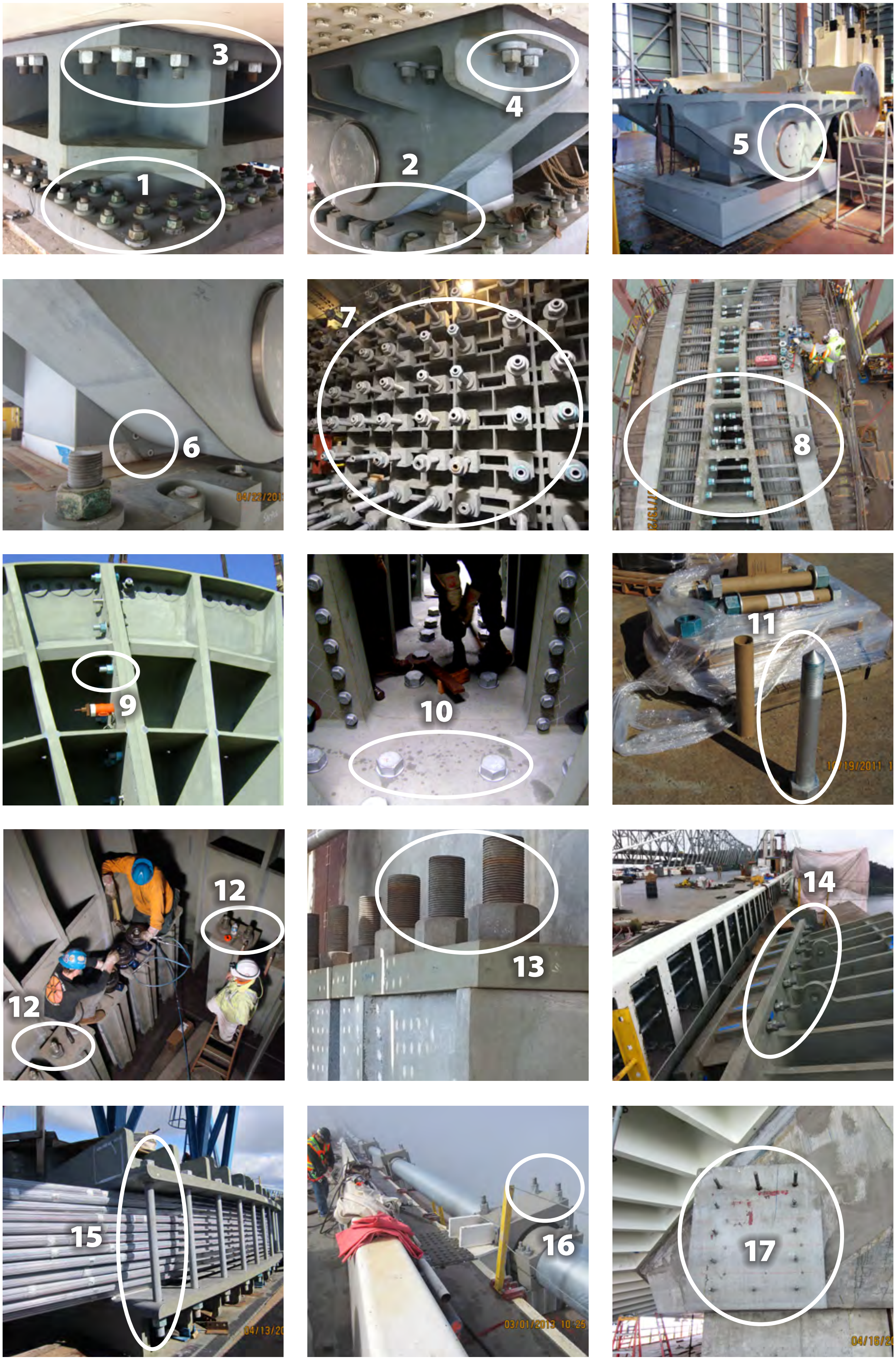


Figure 2 A354 Grade BD Rod Locations on the SAS Bridge (continued)



Definition of Fasteners, Bolts and Rods

Fasteners are steel devices used to mechanically join objects together. Examples of fasteners include rivets, nuts, bolts, studs, screws, eyebolts, nails, threaded rods and washers. Bolts are fasteners that have a head on one end and threads on the other. Anchor bolts are threaded on one end and typically embedded in concrete on the other end, usually with a plate that the head or nut can bear against. Rods are fasteners with threads on each end and typically join items with the use of nuts on each end. For the SAS Bridge, the bolts and rods are made of quenched and tempered steel to ASTM standards that are intended for use in structural connections. For simplicity purposes, this report uses the standard term of "rod." Shown below are construction photos of the Pier E2 shear key A354 grade BD rods (top) and the cable band bolts (bottom).

3. Background on Failure of the Pier E2 A354 Grade BD Shear Key Anchor Rods

Where Are the Failed Rods Located?

Ninety-six (96) high-strength steel rods are installed on the lower housing of shear keys S1 and S2 (Item #1 in Table 1) at Pier E2. These rods were fabricated by Dyson Corporation in Ohio between June 4, 2008 and September 6, 2008 and installed by American Bridge/Fluor Joint Venture, the bridge contractor, in October 2008.

Because of the location of shear keys S1 and S2, directly over the Pier E2 support columns, the design developed by the T.Y. Lin International/Moffatt & Nichol Design Joint Venture called for the rods to be embedded as the concrete pier cap was constructed. This rendered the lower portion of the rods and nuts inaccessible after installation. Figure 3 illustrates Pier E2 and the location of the shear keys, bearings, and their high-strength steel rods. Figure 4 shows the location of the fractured rods.

Figure 3 Bearings (B1-B4) and Shear Keys (S1-S4) in Pier E2

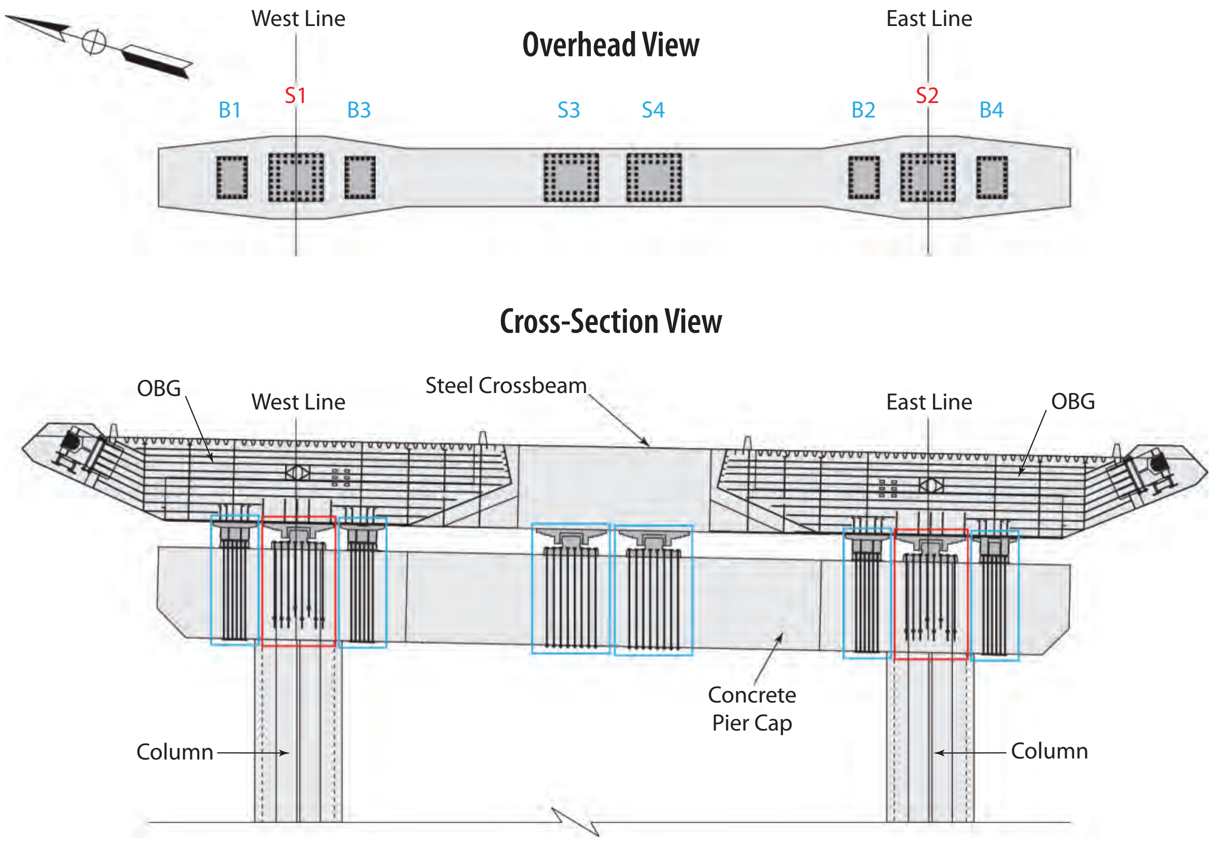
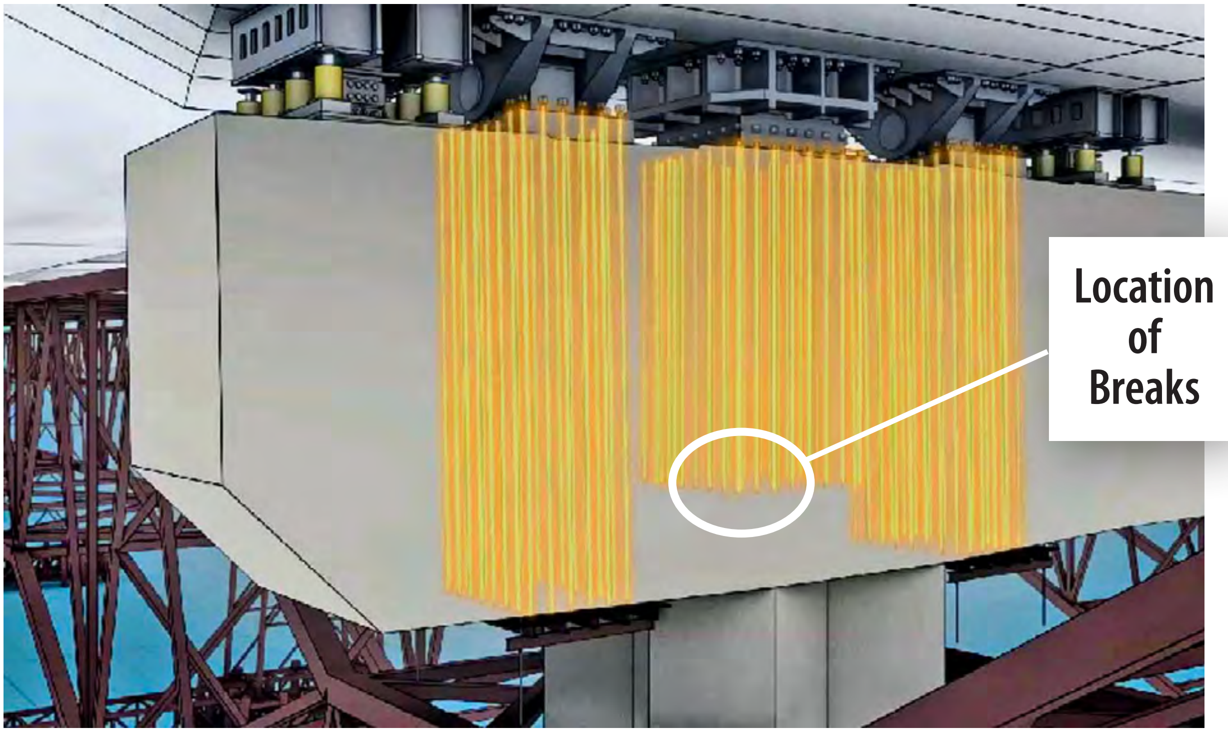


Figure 4 Location of Failed A354 Grade BD Anchor Rods



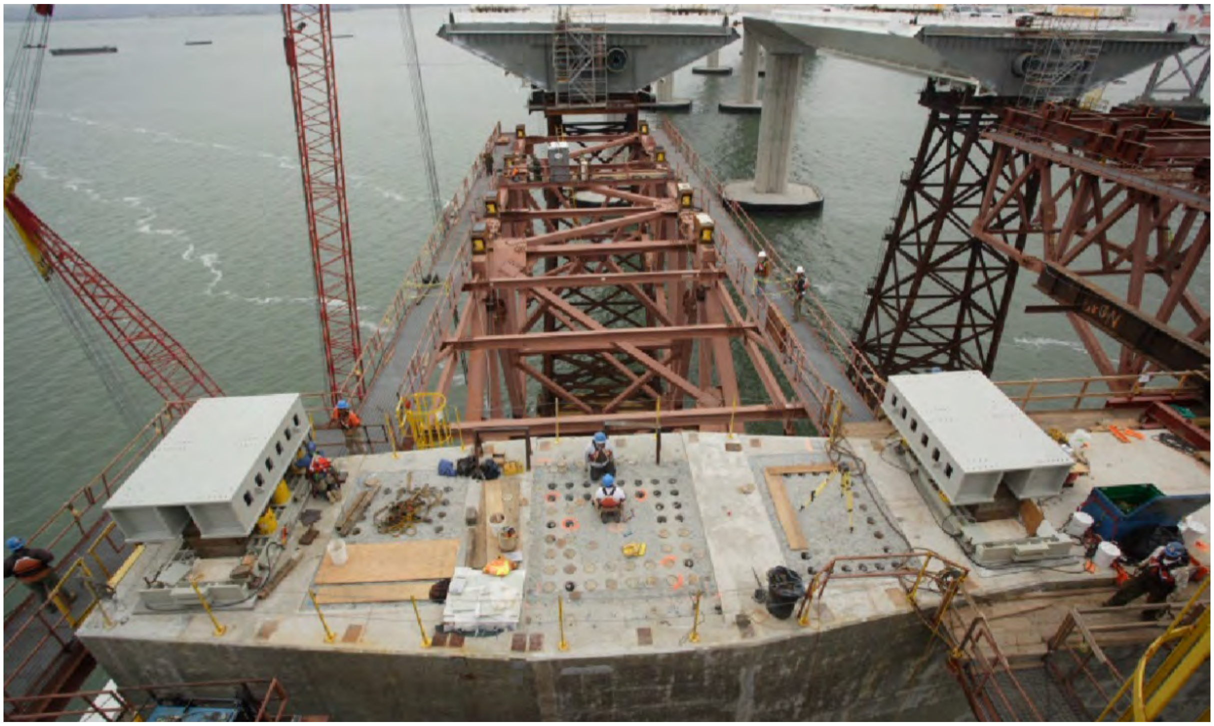
The E2 pier cap, including the embedded 2008 shear key anchor rods, was completed by early 2009. Due to the extended construction schedule, Pier E2 was completed three years before the roadway boxes were erected in place over the pier. This resulted in the anchor rods being exposed to the environment for an extended period of time before the next construction stage, which would tension and grout them in place. This open environment is shown in a Pier E2 construction progress photograph (Figure 5) taken soon after completion of the pier cap. There were no provisions made in the design by the T.Y. Lin International/Moffatt & Nichol Design Joint Venture or the installation procedures prescribed by American Bridge/Fluor Joint Venture to include water drainage or sufficient rain protection to prevent the ingress and accumulation of rainwater or other moisture in the anchor rod housings during this extended period.

What Happened When the Rods Were Tensioned?

On March 1, 2013, following load transfer of the weight of the OBG roadway decks from the temporary falsework onto the main cable, American Bridge/Fluor Joint Venture tensioned the anchor rods at shear key S2. Between March 2 and March 5, 2013, American Bridge/Fluor Joint Venture tensioned the anchor rods at shear key S1. In accordance with contract plans and submittals, the rods were initially loaded to 0.75 Fu (i.e., 75 percent of their specified minimum ultimate tensile strength). Due to seating losses as the load is transferred from the hydraulic jack to the nut, the load then settled to its final design load of 0.68 Fu.

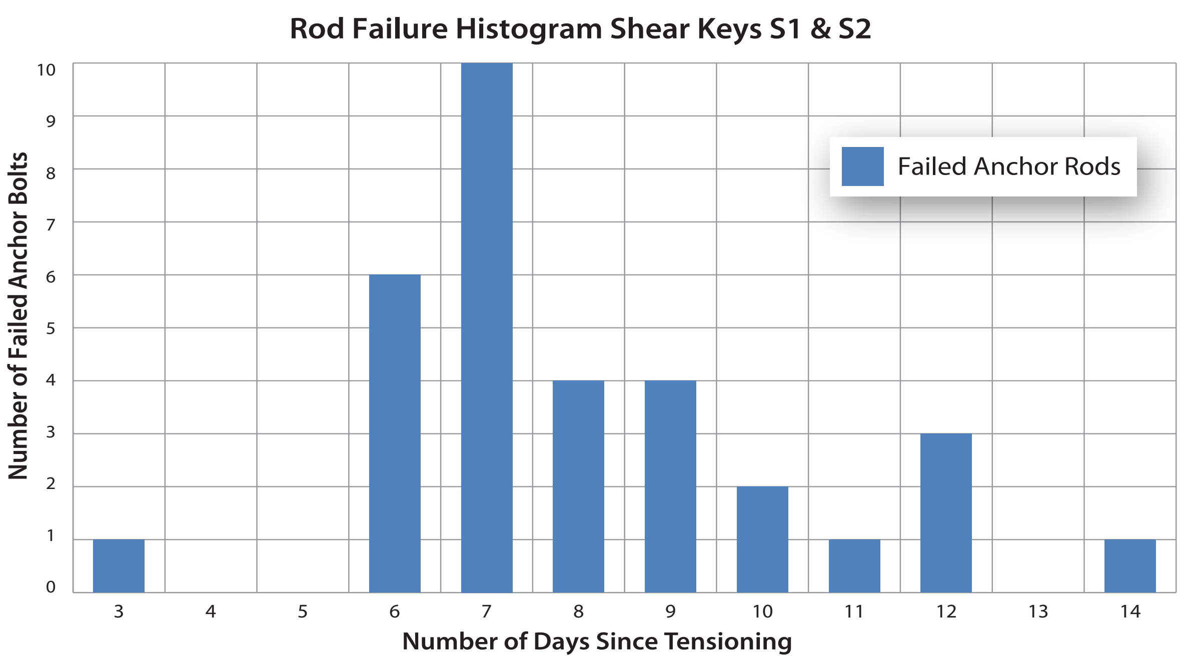
Between March 8, 2013 and March 14, 2013, 32 out of the 96 rods were discovered to have fractured. By March 14, 2013, Caltrans decided to lower the tension of the remaining unbroken rods from the 0.68 Fu to 0.45 Fu to avoid further fractures and to allow for investigation of the cause of the failures. The tension level was reduced on all unbroken rods. If the tension

Figure 5 E2 Pier Cap Construction —
(Center of photograph is the location of future shear key S1)



had not been reduced, it is possible that more of these 2008 high-strength steel rods at shear keys S1 and S2 would have fractured. A chart showing the number of rods that fractured after tensioning began (and the number of days it took them to do so) is shown in Figure 6. Most of these rods have since had their nuts removed and the threaded ends cut off in preparation for the installation of the steel saddle retrofit.

Figure 6 Timeline of 2008 Anchor Rod Fractures After Stressing*



* The time axis shows the number of days after tensioning each individual rod was discovered fractured. Note that the tension in all non-fractured rods was reduced to 0.45 Fu after 14 days.

What Were the Findings of the Metallurgical Analysis Conducted on the Failed Rods?

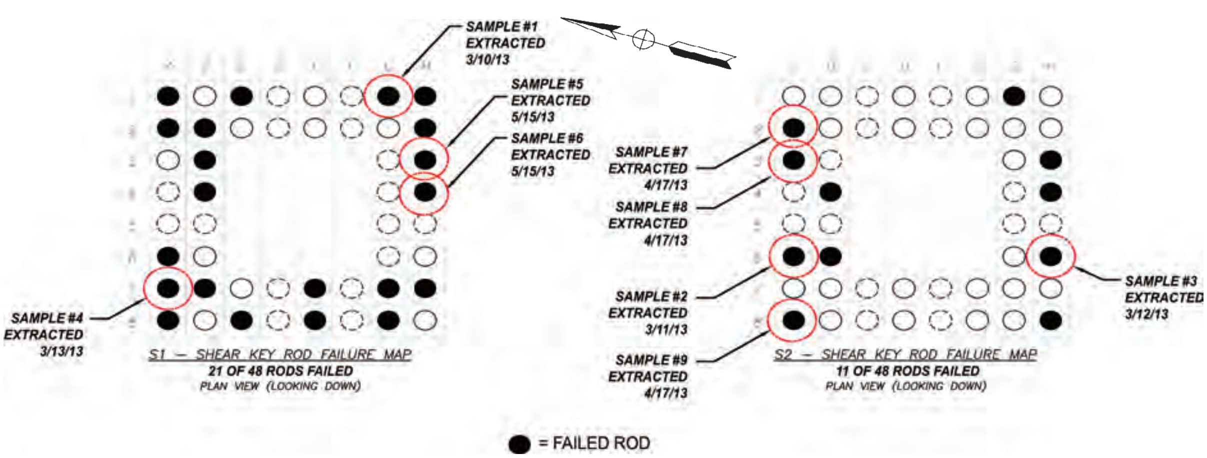
This section of the report provides a summary of the metallurgical analysis and testing performed on a sample of the failed 2008 rods.

A metallurgical investigative team, composed of a consultant to American Bridge/Fluor Joint Venture (Salim Brahimi), a Caltrans metallurgist (Rosme Aguilar), and a consultant to Caltrans who is also principal/founder of Christensen Materials Engineering (Conrad Christensen), was tasked with examining the cause of the failures of the 2008 high-strength steel rods (Item #1 in Table 1). The full report of their findings is contained in Appendix H.13, but a summary is provided below and in Table 2.

The American Bridge/Fluor Joint Venture extracted nine of the 32 fractured rods. The metallurgical team concluded that a sample of nine rods was sufficient to yield reliable results about all the fractured rods based on ASTM F1470 sample sizes, and visual appearance of the fractured faces were found to be very similar. (Sample size required by ASTM F1470 is four rods.) Figure 7 illustrates the location of the 32 fractured rods and the nine extracted rods in shear keys S1 and S2, as listed below. The fractured rods were removed in multiple sections due to the small overhead clearance.

- 3/10/13: Shear Key S1 Location G1 (Sample #1)
- 3/11/13: Shear Key S2 Location A6 (Sample #2)
- 3/12/13: Shear Key S2 Location H6 (Sample #3)
- 3/13/13: Shear Key S1 Location A7 (Sample #4)
- 4/17/13: Shear Key S2 Locations A2, A3, A8 (Samples #7,8,9)
- 5/15/13: Shear Key S1 Locations H3, and H4 (Samples #5,6)

Figure 7 Location of Fractured Rods in Shear Keys S1 and S2



[1]Brahimi, Salim, Rosme Aguilar, and Conrad Christensen. "Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6", May 7, 2013.

Metallurgical Team

Rosme Aguilar, Branch Chief, Caltrans

Mr. Aguilar is the Branch Chief of Caltrans' Structural Materials Testing Branch, responsible for quality assurance testing of structural materials product used in construction projects throughout the state. He has over 30 years of work experience as an Engineer, of which 23 of these years as a Transportation Engineer at Caltrans, 2 years as a Quality Assurance Auditor for the Technological Research Institute of the Venezuelan Petroleum Industry, and 5 years as a Researcher at a Venezuelan steel mill. Mr. Aguilar holds a Master of Science degree in Metallurgy and a Bachelor of Science degree in Metallurgical Engineering from the University of Utah. He is a licensed professional Civil Engineer in the State of California. His areas of expertise and responsibility are Quality Assurance and materials testing, but in addition he has performed or assisted in the performance of numerous materials characterization and failure analysis for Caltrans and other state agencies.

Salim Brahimi, President, IBECA Technologies

Mr. Brahimi is a consultant to American Bridge/Fluor Joint Venture. He is the president of IBECA Technologies. He is a licensed member of the Quebec Order of Professional Engineers and has over 24 years of experience in the fastener industry. Mr. Brahimi holds a Master of Science degree in Materials Engineering from McGill University in Montreal. He is the current chairman of the ASTM Committee F16 on Fasteners. He also serves on the ISO TC2 (Technical Committee on Fasteners), ASTM committees B08 (Coatings), E28 (Mechanical Testing), A01 (Steel), F07 Aerospace and Aircraft, Industrial Fasteners Institute (IFI) Standards and Technical Practices Committee, and the Research Council on Structural Connections (RCSC). Mr. Brahimi is recognized and highly respected throughout the fastener industry as a leading expert in fastener manufacturing, fastener metallurgy, application engineering, corrosion prevention, failure analysis and hydrogen embrittlement.

Conrad Christensen, Principal/Founder, Christensen Materials Engineering

Mr. Christensen is a consultant to Caltrans. He is the principal and founder of Christensen Materials Engineering, which provides laboratory testing and materials engineering services. He holds a Bachelor of Science degree in Materials Science and Engineering from the University of California at Berkeley. He is a licensed professional metallurgical engineer in the States of California and Nevada. He has over 32 years of experience as a metallurgist, specializing in materials testing and failure analysis. His areas of expertise include: microscopic evaluation and characterization of materials, optical microscopy, scanning electron microscopy and fracture analysis.

Table 2 Summary of May 2013 Metallurgical Analysis of Fractured 2008 A354 Grade BD Rods (Two Samples Analyzed)

Test	Description	Results
1. Visual examination/ observations	Anchor rod samples (2) inspected visually	• Observations of both rods indicated an overall brittle appearance. • Evidence indicating that hydrogen-assisted cracks were present in both rods prior to failure. • Cracks initiated and extended from the thread root up to a depth of 0.6 inches in Rod S1-G1, and to a depth of 0.4 inches in Rod S2-A6. • Presence and appearance of cracks, and the delayed nature of the fractures, point to time-dependence of the failure mechanism. • Cracks developed and grew in both rods.
2. Scanning electron microscopy	Fracture surfaces examined at high magnification with a scanning electron microscope (SEM) to further characterize the failure mechanism.	• Observations revealed inter-granular fracture cracking at, and near, the thread root (i.e., crack origin). This indicates a number of brittle fracture mechanisms, including hydrogen-assisted cracking. • Gradually increasing mixed morphology was observed as the crack progressively grew and extended inward from the thread root. • Sudden fast fracture occurred when the crack reached a critical size. • Morphology across the final fast fracture zone was almost exclusively cleavage (brittle fracture mechanism).
3. Microstructural examination	Cross-sections were cut from both rods and metallurgically prepared (i.e., mounted/potted, polished and etched) to examine the structure of the steel on a microscopic scale	• Observations indicated the microstructure was generally tempered martensite, which is the normal structure associated with quenched and tempered American Iron and Steel Institute (AISI) 4140 steel. • However, in some areas, there was evidence of incomplete martensitic transformation, with presence of ferrite and pearlite alternating in banded layers between regions of fully transformed martensite. The banded nature of the microstructure is an indication that the material is not homogeneous.

Test	Description	Results
4. Hardness testing	Rockwell hardness tests were conducted using a conical diamond indenter to correlate to the steel's tensile strength, wear resistance and ductility.	• Results show variation in hardness from 25 Hardness Rockwell C (HRC) (center) to 39 HRC (outer diameter), indicating material not uniformly through-hardened. Completely uniform through-hardening is difficult to achieve in large diameter rods such as these; however, the large disparity in hardness from center to edge indicates the steel may not have had optimal through-thickness hardenability (i.e., optimal and uniform hardness throughout the thickness of the steel) or was improperly heat treated. • The mid-radius Rockwell C hardness values ranged from 32.5 to 36.2 HRC, which are in compliance with the A354 grade BD requirements of 31 to 39 HRC.
5. Tensile testing	Performed on machined test specimens taken from near the outer diameter of each anchor rod.	• Results indicate the material meets yield strength, tensile strength and elongation requirements for A354 grade BD, although elongation (i.e., ductility) was slightly above the minimum limit.
6. Charpy V-Notch Impact testing	Performed on machined Charpy test specimens taken from near the outer diameter of each anchor rod to assess the toughness of the steel.	• Results indicate the material lacks toughness, even when tested at room temperature. Further investigation is required to more fully assess the lack of toughness in the steel. Note: Charpy v-notch impact testing is not a requirement of ASTM A354. However, impact testing characterizes the toughness of the steel, which was called into question by the failures.
7. Chemical analysis	Performed on samples of material from each anchor rod to determine chemical composition.	• Results indicate the chemistry is consistent with AISI 4140 steel and meets the ASTM A354 grade BD requirements.

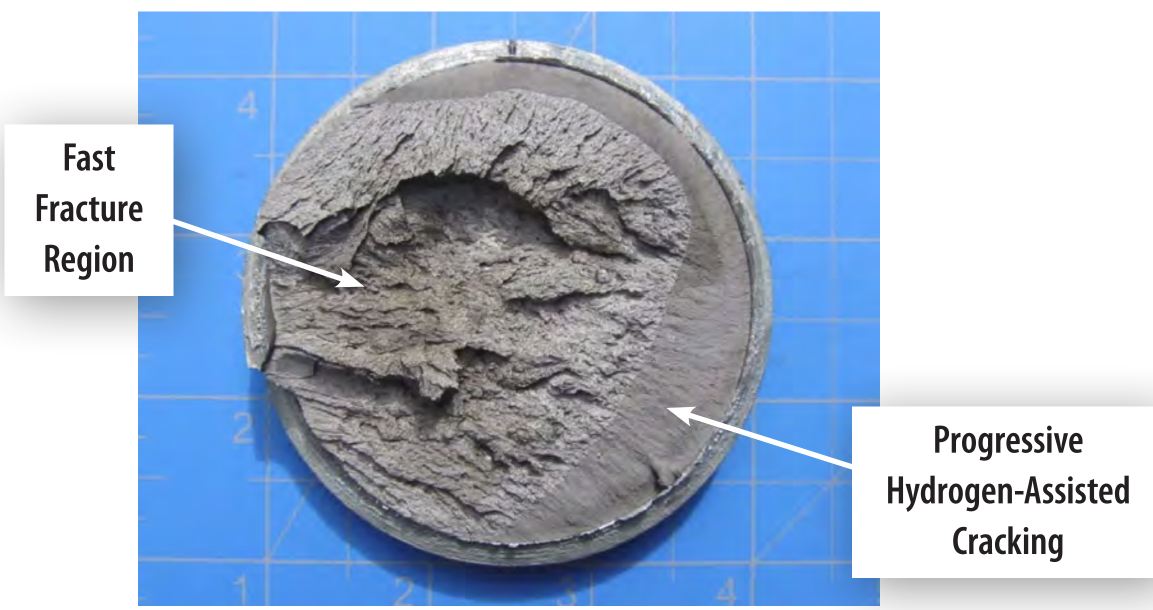
Sections of Samples 1, 2, and 3 — Rod IDs S1-G1, S2-A6, and S2-H6 — were transported to the Christensen Materials Engineering lab in Alamo, California. The remaining six of the nine extracted fractured rods were transported to an American Bridge/Fluor facility at Pier 7 in Oakland, California, and have been tested, per the testing program described in this report.

Three extracted fractured rods were transported to the Christensen Materials Engineering lab. The laboratory observed, through visual examination, that all three fracture surfaces displayed similar characteristics, so two rods, Samples 1 and 2 (S1-G1 and S2-A6), were metallurgically analyzed and destructively tested from March 18, 2013 through April 11, 2013. Table 2 summarizes the different tests that were conducted and the results of each test, which included:

1. Visual examination/observations;
2. Scanning Electron Microscopy (SEM);
3. Microstructural examination;
4. Hardness testing;
5. Tensile testing;
6. Charpy V-Notch Impact testing; and
7. Chemical analysis.

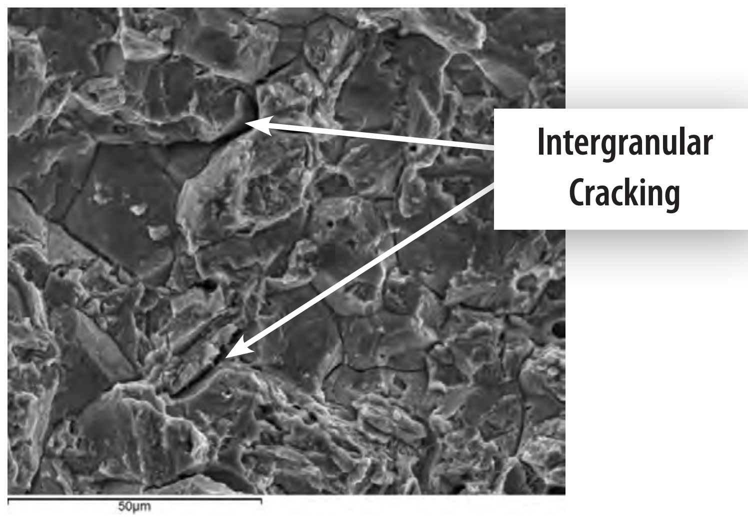
1 Visual examination/observations: Figure 8 is a photograph of fractured Rod S1-G1, after cleaning. The metallurgical team found that both rods had an overall brittle appearance and showed evidence of hydrogen-assisted cracks.

Figure 8 Fracture Surface of Rod S1-G1 After Cleaning



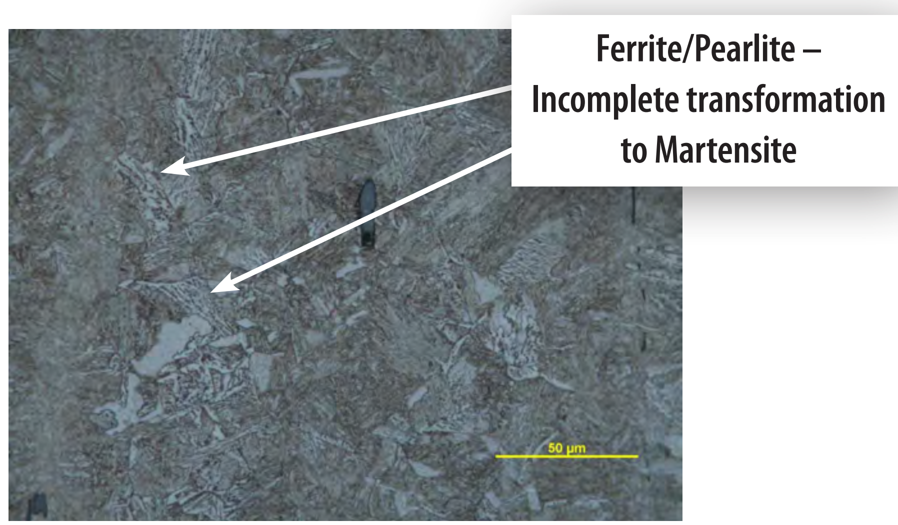
2 Scanning Electron Microscopy (SEM): Following visual observations, the fracture surfaces were examined at high magnification with a scanning electron microscope (SEM). Figure 9 is an SEM image of Rod S1-G1 at high magnification, which shows intergranular cracking at, and near, the crack origin. Intergranular cracking is a characteristic feature indicative of a number of brittle fracture mechanisms, including hydrogen-assisted cracking.

Figure 9 SEM Image of Rod S1-G1 Showing Intergranular Fracture Features



3 Microstructural examination: Following the SEM examination, cross-sections were cut from both rods and metallurgically prepared to examine the structure of the steel on a microscopic scale. The results of this examination (Figure 10) indicate the material is not homogeneous (i.e., not uniform in metallurgical structure across the examined sample of rod), as evidenced by the presence of ferrite and pearlite in between layers of martensite.

Figure 10 Microstructural Examination Indicating Non-Homogeneous Material



4 **Hardness testing:** The Rockwell C hardness test is a technique that assesses a material's tensile strength, wear resistance and ductility. Samples were machined at Christensen Materials Labs and tests were performed in Hayward, California by Anamet Inc., where Rockwell C hardness measurements were made across the diameter and at mid-radius locations of both rods. Figures 11 and 12 illustrate the results of the Rockwell hardness tests conducted on Rod S1-G1 and Rod S2-A6, respectively. The results of the Rockwell hardness test show variation in hardness, with the outer diameter approaching 39 HRC (high hardness is generally considered greater than 35 HRC). The center hardness drops to as low as 25 HRC, indicating the material was not uniformly through-hardened. The metallurgical report states that completely uniform through-hardening is difficult to achieve in large diameter rods such as these; however, the large disparity in hardness from center to edge indicates that the steel may not have had optimal through-thickness hardenability or was improperly heat-treated. ASTM A354 for grade BD specifies a maximum rod hardness of 39 HRC, as shown by the solid red line in Figures 11 (Rod S1-G1) and 12 (Rod S2-A6).

Figure 11 Rockwell Hardness Test Results — Rod S1-G1

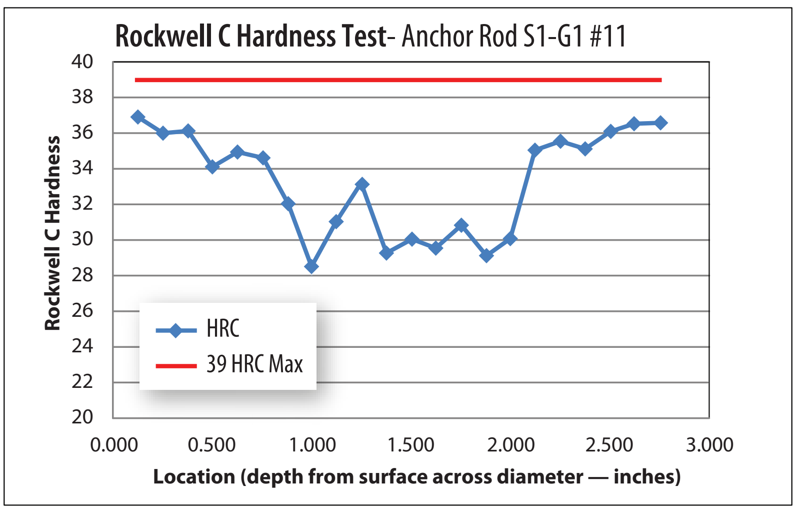
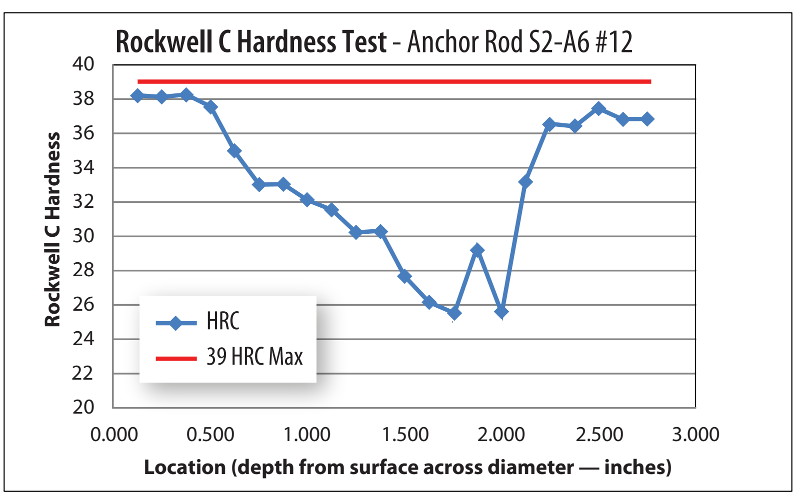


Figure 12 Rockwell Hardness Test Results — Rod S2-A6



5 **Tensile testing:** To measure the material's other properties, a tensile test was conducted, where the rods were subjected to a controlled tension until failure. Tensile testing was performed by Anamet, Inc. on two specimens taken from near the outer diameter of each fractured rod. The metallurgical team found that results indicated the material meets yield strength, tensile strength and elongation (i.e., ductility) requirements for A354 grade BD, although elongation was slightly above the minimum limit.

6 **Charpy V-Notch Impact testing:** To assess the toughness of the steel, Charpy V-Notch impact testing was performed. A rectangular specimen with a 'V' shaped notch cut into the midpoint of the length is struck by a pendulum-mounted striker to determine the amount of energy absorbed by a material during a fracture. The metallurgical team found that results obtained for these rods ranged from 13.5 to 17.7 ft-lb when tested at 40° F. ASTM A354 does not have a Charpy V-Notch testing requirement, so as a useful comparison, the minimum requirement for general grade steel is usually 20 ft-lb when tested at room temperature and some steel grades have toughness requirements as high as 60 ft-lb (minimum). The results for the 2008 rods are low, demonstrating that these rods exhibit a lack of toughness.

7 **Chemical Analysis:** Finally, to determine the chemical composition of the fractured rods, a chemical analysis was performed on samples of material from each anchor rod. The findings indicate the chemical composition of the rods meets the ASTM A354 grade BD requirements.

Based on its examination of two of the extracted high-strength steel rods (S1-G1 and S2-A6), the metallurgical investigation team on April 23, 2013, found that:

1) The chemical composition was compliant with the ASTM standards for A354 rods, even though the range of some of the tests placed individual test results outside of the specification but were statistically acceptable to the ASTM standards;
2) Despite meeting ASTM standards, the A354 grade BD material was susceptible to hydrogen embrittlement;
3) The material was not homogeneous (i.e., composed of elements that are not all of the same kind) with a mixture of ferrite, pearlite and transformed martensite banding providing varying mechanical properties (hence the wide range in test results);
4) There was evidence of elongated inclusions (i.e., the presence of particles in a long and thin pattern) laying in the same direction as the ferrite, pearlite and transformed martensite banding;
5) The hardness of the outer half-inch of the rods was significantly different than the inner two-inch core; therefore, the elasticity and distribution of the load within the material may vary; and
6) There was no evidence of surface corrosion near the fractures. (Subsequent visual examinations of the other six extracted rods confirmed this finding to be representative of all nine extracted rods.)

The metallurgical report's conclusions are quoted below:

1) *The anchor rods failed as a result of hydrogen embrittlement (HE), resulting from the applied tensile load and from hydrogen that was already present and available in the rod material as they were tensioned. The root cause of the failures is attributed to higher than normal susceptibility of the steel to hydrogen embrittlement.*
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 has caused the anchor rods to be susceptible to HE failure.*
4) *Procurement of future A354 grade BD anchor rods should include a number of standard supplemental requirements to assure against HE failure. The appropriate specification of supplemental requirements is currently under review.*

Did Other Factors Contribute to the Rod Failures?

The metallurgical report concluded that the primary cause for the failure was the susceptibility of the 2008 A354 grade BD rods to hydrogen embrittlement. The resultant microstructure of the rods was not homogeneous and the tensile strength significantly exceeded the minimum specified requirements. These properties are developed in the steel during the fabrication of the rod.

As covered later in this report, a number of other factors may also have contributed to the failure of the 2008 A354 grade BD rods. When combined with the microstructure not being homogeneous, these factors resulted in a very high failure rate of the 2008 rods. These other factors include:

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

What Is Hydrogen Embrittlement?

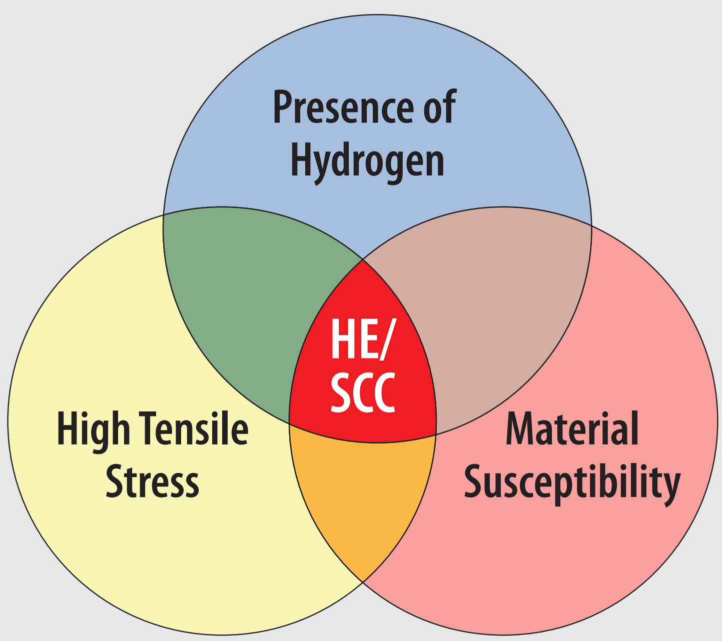
Hydrogen embrittlement (HE) is the process by which metals, including high-strength steel, become brittle and fracture following exposure to hydrogen. Excess hydrogen in a metal can migrate on an atomic level and accumulate, causing weakness/embrittlement of the material when under high stress. The embrittlement is time-dependent and typically occurs within days to a couple of weeks of stressing.

HE can seriously reduce ductility and load-bearing capacity, causing cracking and brittle failures at stresses below the yield stress of susceptible materials. High-strength steels exceeding a tensile strength of 150 ksi possess a metallurgical structure that has an affinity for hydrogen, which is increased through the application of heat usually during the manufacturing process, or when subjected to high levels of stress. There is also a risk of internal HE in high-strength steel rods having a specified minimum hardness of 33 HRC. While the specified hardness range for ASTM 354 grade BD bolts and rods is between 31 HRC and 39 HRC, ASTM F2329 emphasizes the risk of embrittlement for high-strength steel at 33 HRC and above.

The threaded section of a fastener assembly is most susceptible to hydrogen embrittlement due to the high stress concentration and the ability of hydrogen to migrate to this location.

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

Causes of Hydrogen Embrittlement (HE) or Stress Corrosion Cracking (SCC)



4. Question 1: What Led to the Failure of the A354 Grade BD Steel Rods on Shear Keys S1 and S2 at Pier E2?

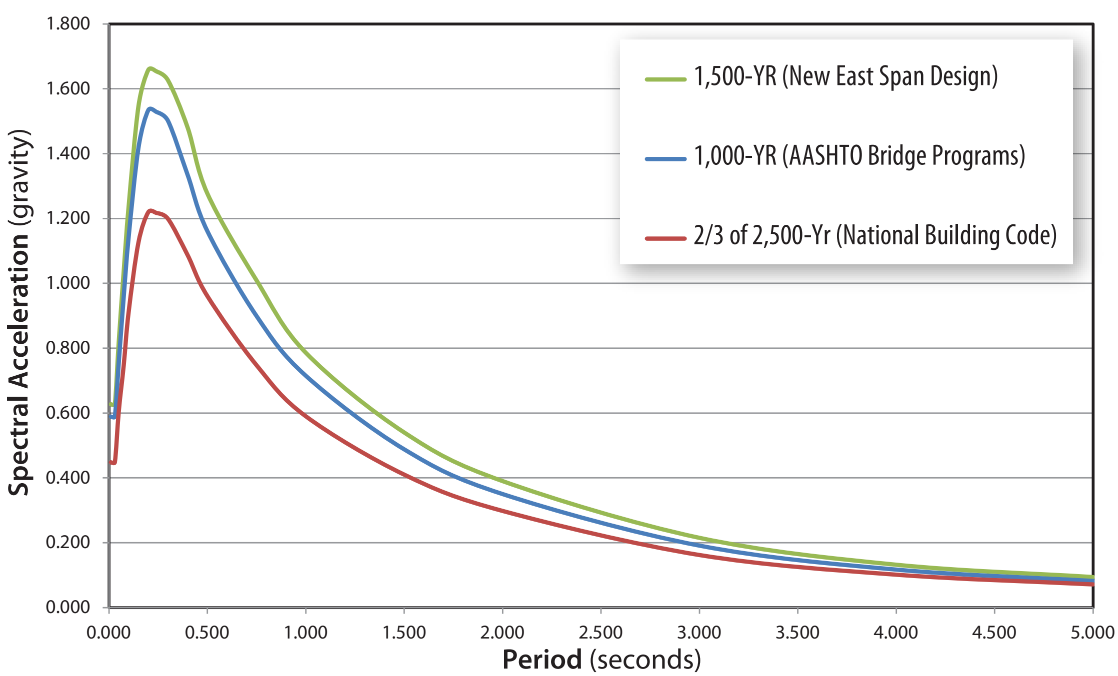
Design & Specifications

Why Are High-Strength Steel Rods Required?

The San Francisco-Oakland Bay Bridge was designated by Caltrans in October 1994 as an important "lifeline" structure because of its location along crucial transportation corridors. In short, this means that the Bay Bridge is to provide a high level of post-earthquake transportation service for emergency response and support for the safety and economic livelihood of the Bay Area. Combined with the West Span seismic retrofit, the retrofit of the west Yerba Buena Island viaduct and Yerba Buena Island tunnel, and the West Approach replacement, the replacement of the East Span would complete the lifeline connection across San Francisco Bay.

Because of the Bay Bridge's designation as a lifeline structure, Caltrans required that the East Span Replacement Project incorporate design elements that exceed the requirements of standard seismic bridge design. The East Span Replacement Project was designed to withstand massive seismic accelerations expected to only reoccur once every 1,500 years. The bridge's expected life span is 150 years, so there is approximately a 10 percent chance that such an earthquake would happen during its life span. As indicated in Figure 13, the design ground motions from a 1,500-year return period earthquake are greater than design ground motions from the American Association of State Highway and Transportation Officials (AASHTO)'s current standard of a 1,000-year return period earthquake for highway bridges. They also exceed the standard set by the National Building Code for modern building construction.

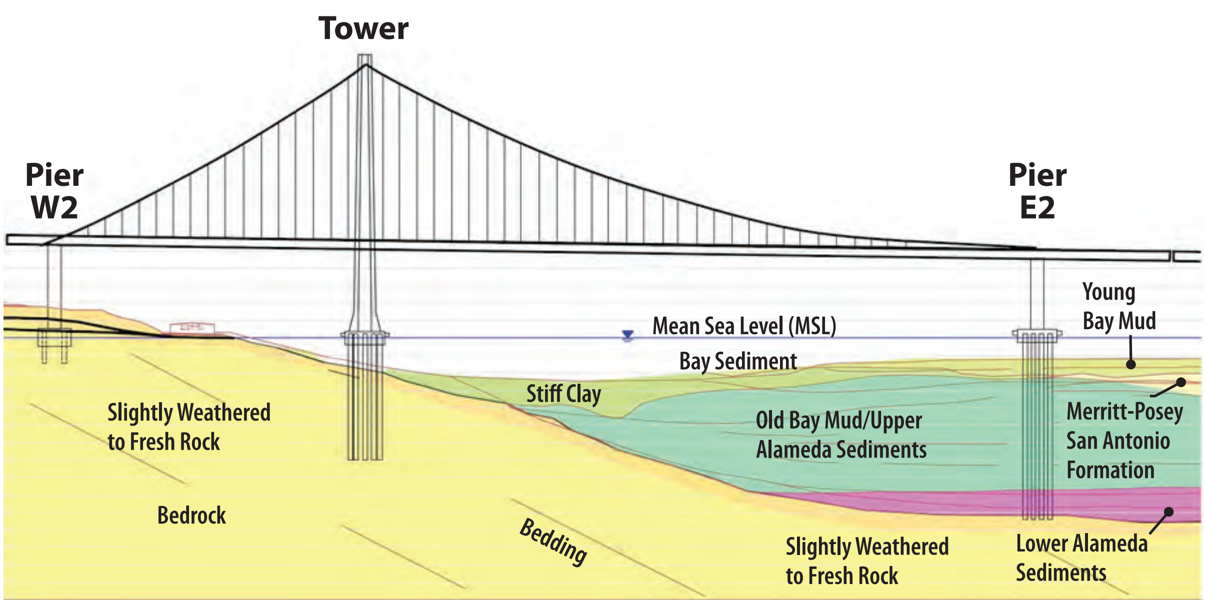
Figure 13 Comparison of New East Span Design Ground Motions to Other Standards



The geology and geotechnical conditions for the East Span Replacement Project were some of the challenges considered in the bridge design. As illustrated in Figure 14, the marine foundations of the main tower (T1) and west pier (W2) of the SAS Bridge are in bedrock, while the foundation of the east pier (E2) sits in bay sediments. Specifically, Pier E2 sits in the Alameda formation, which is the oldest of five formations that make up the bay sediments and is composed of layers of dense clays and sands. This means that the T1 and W2 piers will behave and shake differently than the E2 pier, if left unmitigated. To keep Pier E2 moving in harmony with the rest of the bridge during a seismic event, bridge designers determined a strong connection to the east pier was needed to withstand the high seismic loads.

To make these strong connections, and to ensure the lifeline seismic performance expected of the new east span, the T.Y. Lin International/Moffatt & Nichol Design Joint Venture's design required the use of high-strength steel rods at several locations on the SAS: Parallel Wire Strand (PWS) Anchor Rod, Cable Band Anchor Rods, East Saddle Tie Rods, East Saddle Anchor Rods, Tower Anchor Rods, Tower Saddle Tie Rods, and Pier E2 Bearing and Shear Key Anchor Rods. High-strength steel rods are commonly used throughout the bridge construction industry to make strong physical connections at high-load locations. High-loads are a function of a number of factors in design, including type of bridge, specified design loads, and site-specific requirements, like geology. On the SAS Bridge, high-load locations are inevitable given the higher-than-standard specified seismic design criteria and the challenging geology around the bridge. This, in turn, has required high pre-loads, or tensioning, to be applied for connecting restraining elements such as shear keys to provide slip resistance and minimum deformation.

Figure 14 Geology Conditions at the SAS Bridge



San Francisco-Oakland Bay Bridge Designated as "Lifeline Bridge"

The San Francisco-Oakland Bay Bridge was designated by Caltrans as a "lifeline bridge." Lifeline bridges are those whose economic consequences of failure are large, or that provide secondary life safety or are designated as important by local emergency officials. The San Francisco-Oakland Bay Bridge qualifies as a lifeline bridge, because following a major earthquake, it is expected to be restored to immediate service level — which means full access to normal traffic available almost immediately — and to be used as an emergency lifeline route.

Date	Event
May 1990	In its "Competing Against Time" report, Governor Deukmejian's Board of Inquiry – which was tasked with investigating why the Cypress Viaduct and Bay Bridge failed during the 1989 Loma Prieta earthquake – recommended that the state "require that seismic safety be a paramount concern in the design and construction of all state-owned structures. Specific goals of this policy shall be that the state-owned structures be seismically safe and that important State-owned structures maintain their function after earthquakes."[2]
June 1990	Governor Deukmejian issued Executive Order D-86-90 that states: "It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings."
September 1990	Caltrans appointed the Seismic Advisory Board, as directed by Governor Deukmejian in Executive Order D-86-90, to provide continued, focused evaluation of Caltrans seismic policy and technical procedures.
October 1994	In its "The Continuing Challenge" report to the Caltrans Director following the 1994 Northridge earthquake, the Seismic Advisory Board recommended that more emphasis must be given to starting toll bridge retrofit construction projects on as rapid a schedule as practical. The Bay Bridge was identified as a lifeline bridge.[3]

[2]Governor Deukmejian's Board of Inquiry (May 1990). *"Competing Against Time,"* p. 9
[3]Seismic Advisory Board (October 1994). *"The Continuing Challenge: The Northridge Earthquake of January 17, 1994,"* p. 8.

What High-Strength Steel Rod Options Were Available?

Table 3 shows high-strength fastener options that were available for consideration by bridge engineers for use on the SAS Bridge.

ASTM A354 is an American Society for Testing and Materials (ASTM) International standard that defines chemical and mechanical properties for a specific alloy for steel bolts, screws, studs and other externally threaded rods. A354 Specifications cover grade BC and grade BD anchor bolts, threaded rods and headed bolts for sizes 4-inch and under in diameter[4]. (ASTM A490 Specification covers only hexagon headed bolts up to 1 ½ -inch diameter.)

A354 grade BD rods feature minimum tensile strengths of 150 ksi for ¼-inch to 2½-inch diameter rods and 140 ksi for 2¾-inch to 4-inch diameters.

Other options for bolts and rods in excess of 1½-inch diameter include lower-strength A354 grade BC rods, with minimum tensile strength of 115 ksi, or F1554 grade 105 rods, with minimum tensile strength of 125 ksi. The lower tensile strengths of A354 grade BC or F1554 rods, however, mean more rods would be needed to do the same job a smaller number of A354 grade BD rods can do.

Equivalent-strength alternatives to the A354 grade BD rod are ASTM A722 and Macalloy rods. Williams Form Engineering Corporation and Dywidag Systems International both manufacture ASTM A722 fasteners but in 2001 neither produced rods that were as large as 3 inches in diameter[5]. In order to use A722 rods, bridge designers would have had to accommodate multiple potential vendor connections.

Each rod type has different material properties and associated pros and cons. Table 3 provides a comparison between various rod types.

[4] For simplicity purposes, this report uses the term "rod."

[5] Letter from T.Y. Lin International/Moffatt & Nichol (September 2001) to Caltrans (Dr. Brian Maroney) regarding approval to use sole-source for Macalloy high-strength prestressing bars.

Table 3 Comparison of High-Strength Steel Rod Types

Rod Materials Type	Minimum Tensile Strength (Ksi)	Equivalent Diameter (in)	Pros	Cons
A354 Grade BD	140	3	• High strength • Generally available • Has a minimum specified tensile strength between 140 and 150 ksi	• Susceptible to hydrogen embrittlement without due care when galvanizing
A354 Grade BC	125	3.5	• Generally available • Less susceptible to hydrogen embrittlement • Can be galvanized without cautions • Has a minimum specified tensile strength between 115 and 125 ksi	• Lower strength (than BD) • Would require more rods and larger connecting surfaces (than BD)
F1554	125	3	• Generally available • Less susceptible to hydrogen embrittlement • Can be galvanized without cautions • Has a minimum specified tensile strength between 125 and 150 ksi	• Lower strength (than BD) Would require more rods and larger connecting surfaces (than BD)
A722	150	3	• High strength • Has a minimum specified tensile strength of 150 ksi	• Proprietary connectors might require waiver from sole-source restrictions • No domestic suppliers produced 3-inch A722 rods, proprietary or otherwise at the time specifications were prepared • Only available through certain suppliers

Why Were A354 Grade BD Steel Rods Selected for the SAS Bridge?

To make the strong connections, the designer selected A354 grade BD steel rods. The SAS Design Criteria, which were finalized on July 15, 2002, specify the use of ASTM A354 grade BD for a number of the structural steel connection locations. The criteria do not specifically discuss corrosion protection for any of the fasteners listed in the project-specific design criteria. Corrosion protection is typically covered in Caltrans construction contract specifications.

The highest-strength steel rods were required by the bridge design due to the low number of rod locations within the concrete pier cap at E2. At the east pier, if more rod locations were designed for, it would have required a larger upper and lower shear key and bearing base plate, which may have resulted in a larger pier cap and cross beam. These larger elements would have resulted in more mass, which would have affected the seismic forces that need to be accounted for in the design.

A354 grade BD steel is a high-strength material that is used in construction on very large bridges to make bonded connections when high loads are expected. Ungalvanized A354 grade BD rods, with high quality corrosion protection systems, have been used on comparable West Coast bridge projects including the retrofit of the Golden Gate Bridge and the construction of the new Tacoma-Narrows Suspension Bridge in the strait of Puget Sound in Pierce County, Washington.

Beyond the design requirements for a high-strength material, the decision to utilize A354 grade BD steel was due, in part, to sole-source restrictions that discouraged use of proprietary rods, unless it could be established that there was no alternative. A354 grade BD rods are generally available and could be competitively bid. To source alternative materials, bridge designers would have had to sole-source a vendor to complete the rod connector design, pass design responsibilities to the contractor to complete the connector design, or design to accommodate multiple vendor connections. Nonetheless, Caltrans did sole-source materials elsewhere on the project, including: 1) Macalloy bars for the western anchor connection of the SAS Bridge to Pier W2 and seismic Hinge K pipe beam anchors between Pier W2 and the deck of the Yerba Buena Island Transition Structure; 2) piston motor driven trolleys, the passive trolleys, and the brake trolleys for the SAS Maintenance Traveller; and 3) the components for epoxy asphalt binder and epoxy asphalt bond coat used on the roadway surface. In each instance sole-source waivers were requested and obtained, establishing the lack of any comparable item that could be competitively bid. However, non-proprietary materials are typically specified whenever possible.

An example of sole-source for the new East Span project relates to rods located at the base of Pier W2 tiedown. The jack size requirements and space limitations at this location required the use of 75mm high-strength steel conforming to ASTM A722. The Design Engineer contacted four major manufacturers and none manufactured rods that conformed to these specifications, except Macalloy. A sole-source approval was requested by the Engineer and subsequently granted by Caltrans and FHWA.

Sole-Source Restrictions

Most public contract work in California is controlled by the provisions of the California Public Contract Code. This code represents the efforts of the California legislature to gather into one place all statutory enactments that deal with public contracts, such as laws that govern competitive bidding. Per Public Contract Code, Section 3400:

> *3400. (b) No agency of the state, nor any political subdivision, municipal corporation, or district, nor any public officer or person charged with the letting of contracts for the construction, alteration, or repair of public works, shall draft or cause to be drafted specifications for bids, in connection with the construction, alteration, or repair of public works, (1) in a manner that limits the bidding, directly or indirectly, to any one specific concern, or (2) calling for a designated material, product, thing, or service by specific brand or trade name unless the specification is followed by the words "or equal" so that bidders may furnish any equal material, product, thing, or service."*

However, in some cases, the above code section is not applicable, such as when the awarding authority determines that a particular material or product is the only one that will fulfill the needs of the project (referred to as "sole-source"). Caltrans' Office of Structure Design requires that the Specifications Engineer obtain the necessary approvals from the Chief, Division of Structures and the FHWA. In addition, if a product is required for which there is only one known manufacturer, special firm price quotes must be obtained from the manufacturer for inclusion in the contract documents.

At the federal level, the Federal Highway Administration regulation in 23 CFR 635.411, "Material or product selection," prohibits the expenditure of Federal-aid funds on a Federal-aid highway project "for any premium or royalty on any patented or proprietary material, specification, or process" (referred to hereafter as "proprietary product"), unless specific conditions are met. This regulation is intended to ensure competition in the selection of materials, products, and processes while also allowing the opportunity for innovation where there is a reasonable potential for improved performance. Also, in accordance with 23 CFR 635.411, State Departments of Transportation (DOTs) may specify a higher standard of performance (i.e., above what would normally be set) on certain construction projects even though it would result in a single product being available.

An example of sole-source procurement for the new East Span project relates to rods located at the base of Pier W2 tiedown. The jack size requirements and space limitations at this location required the use of 75mm high-strength steel conforming to ASTM A722. The Design Engineer contacted four major manufacturers and none manufactured rods that conformed to these specifications, except Macalloy. A sole-source approval was requested by the Engineer and subsequently granted by Caltrans and FHWA.

How Should the A354 Grade BD Steel Rods Be Protected From Corrosion?

When exposed to the atmosphere, all metals, except precious metals such as gold and silver, have a natural tendency to corrode. Steel is an excellent building material, but it is inevitable that steel will corrode. The most commonly used method to adequately protect exposed steel rods and bolts from corrosion is to galvanize them by applying a zinc coating. However, galvanizing is not the only method for providing corrosion protection. Other methods include, but are not limited to, sheathing the rods in grease or grout, paint, or other coatings like Geomet® or Dacromet®. Each option provides different levels of corrosion protection and challenges for application.

What Are the Risks Associated With Galvanization?

The two most common galvanization methods for A354 steel rods are hot-dip galvanizing and mechanical galvanizing. Table 4 summarizes the differences between the two galvanization methods. In general, a hot-dip galvanization process requires the use of heat in which the fabricated steel is dipped into a bath of molten zinc at approximately 850 °F. High-strength steels over 150 ksi possess a metallurgical structure that can have an affinity for hydrogen, which is increased through the application of heat or when subjected to high levels of stress. A mechanical galvanization process does not require heat and is performed at room temperature by tumbling the fabricated steel in a barrel to cold-weld the zinc coating onto the surface.

While hot-dip galvanization may be more cost-effective and provide better coverage of the zinc coating, careful attention must be paid to the application of heat. Too much heat could cause the release of internal hydrogen and when encapsulated in the zinc coating increases the risk of hydrogen embrittlement. While the use of mechanical galvanization at room temperature may minimize the affinity for hydrogen, the process of tumbling end-over-end and rolling steel pieces that are long, heavy, or have large diameters may be difficult to do for most galvanizers. In addition, tumbling threaded rods can damage the threads.

Table 4 Galvanizing Methods

Method	Description	Process
Hot-Dip Galvanizing	A process of dipping fabricated steel into a kettle or bath of molten zinc at a temperature of around 850 °F. While the steel is in the kettle, the iron metallurgically reacts with the molten zinc to form a tightly bonded alloy coating that provides corrosion protection to the steel.	1. Steel is cleaned using a caustic solution to remove oil/grease, dirt, and paint. 2. The caustic cleaning solution is rinsed off. 3. The steel is pickled in an acidic solution (typically for 20 minutes) to remove mill scale.** 4. The pickling solution is rinsed off.** 5. A flux, often zinc ammonium chloride, is applied to the steel to inhibit oxidation of the cleaned surface upon exposure to air. The flux aids the process of the liquid zinc wetting and adhering to the steel. 6. The steel is dipped into the molten zinc bath and held there until the temperature of the steel equilibrates with that of the bath. 7. The steel is cooled in a quench tank to reduce its temperature and inhibit undesirable reactions of the newly-formed coating with the atmosphere. **When there is a risk of hydrogen embrittlement, these operations are replaced by dry abrasive cleaning (grit blasting) and flash pickle (less than 30 seconds) wash/rinse.
Mechanical Galvanizing	A room-temperature process in which steel pieces are tumbled in a barrel with a mixture of water, zinc powder, other chemicals, and glass impact beads. As the parts are tumbled in the slurry, the zinc is “cold welded” to the piece without the use of heat.	1. The steel piece is cleaned either by an acid pickling process or by using a degreaser/descaler. 2. The piece is rinsed. 3. The piece is then tumbled in a mixture of various-sized glass beads and a predetermined amount of water, with small amounts of chemicals and powdered zinc added periodically. Collisions between the glass beads, zinc, and the piece cause a cold-welding process that applies the zinc coating. 4. Powdered zinc is added until the specified thickness is attained.

Regardless of the kind of galvanization method used, the steel is subjected to a cleaning process prior to galvanizing to remove surface impurities. There are two methods to prepare the steel for galvanizing, depending on the tensile strength of the steel.

For high-strength steels that are not susceptible to hydrogen embrittlement (e.g., A354 grade BC steels), the steel can go through a pickling process, followed by a water bath rinse. Pickling is a process in which a solution containing strong acids (usually a hydrochloric acid) is used to remove the surface impurities of the steel. The steel being pickled typically remains in the acid solution for 20 minutes depending upon the thickness of the oxide layer. When dry blast (abrasive) cleaning in-lieu of pickling, the steel is first dry blast cleaned then flash pickled for less than 30 seconds.

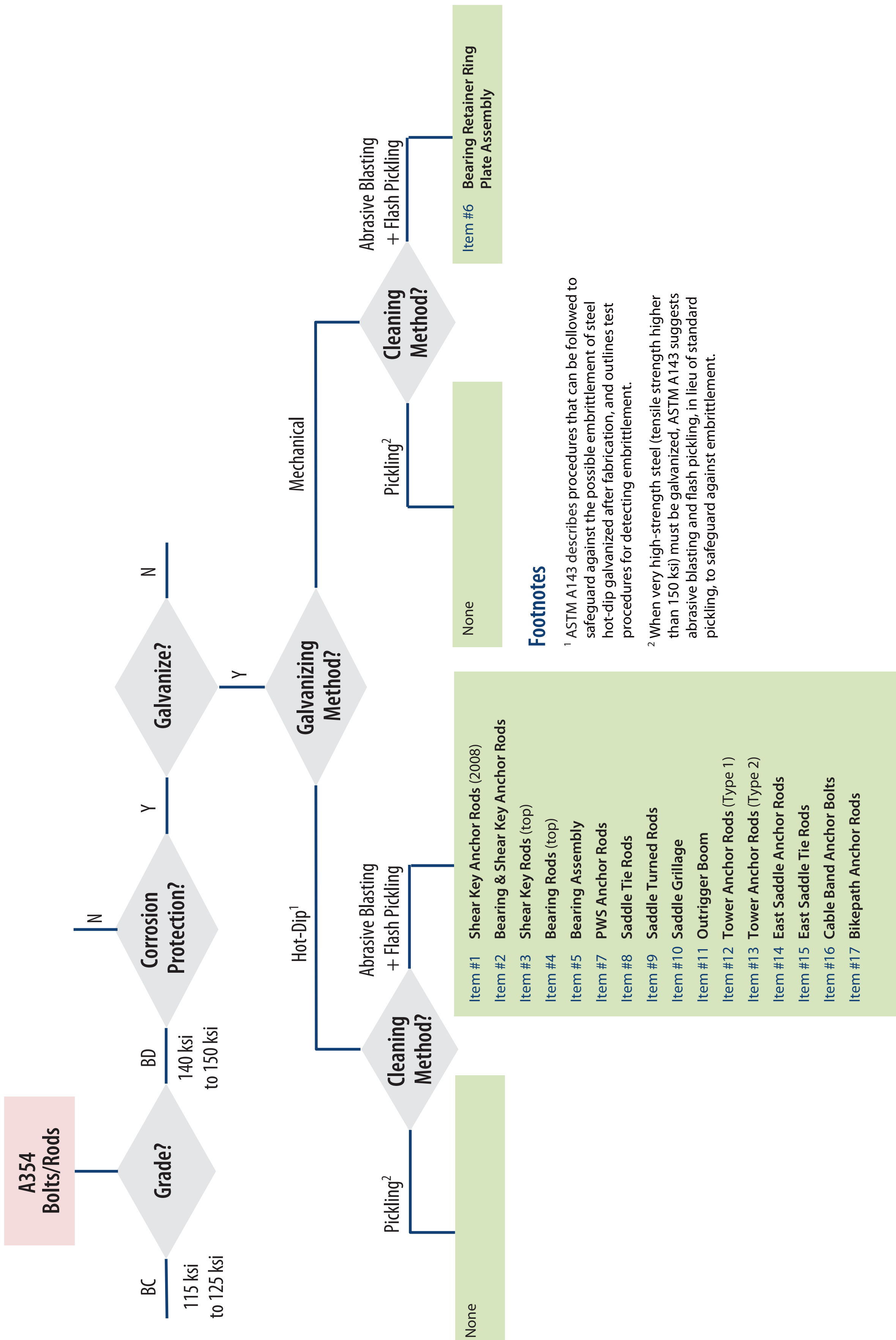
For high-strength steels that are susceptible to hydrogen embrittlement (e.g. A354 grade BD steel), the pickling process and water rinse can be replaced by abrasive blasting and flash pickling (less than 30-second dip) to avoid the potential absorption of hydrogen by the steel, which can occur through the lengthy initial pickling process.

The galvanization process used for the A354 grade BD steel rods placed on the SAS Bridge is illustrated in Figure 15. Project documents indicate that all A354 grade BD steel rods were cleaned by the abrasive blast and flash pickling process and then hot-dip galvanized, except for Item #6 rods which were mechanically galvanized. The flash pickling process minimizes the potential for hydrogen absorption.

The steel fabrication industry has developed and published Standards and Codes of Practice, such as ASTM A143 (Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products & Procedure for Detecting Embrittlement), which provides guidance on how to reduce the risks associated with galvanizing high-strength steels. Excerpts from ASTM A143:

> *7.1 Hydrogen can be absorbed during pickling and in some instances, noted in 4.2, may contribute to embrittlement of the galvanized product. The likelihood of this, or of surface cracking occurring, is increased by excessive pickling temperature, prolonged pickling time and poor inhibition of the hydrogen absorbed during pickling.*
>
> *7.2 Abrasive blast cleaning followed by flash pickling may also be employed when over-pickling is of concern or when very high strength steel, ultimate tensile strength higher than 150 ksi, must be galvanized. The flash pickling after abrasive blast cleaning is used to remove any final traces of blast media before hot-dip galvanizing.*

Figure 15 Galvanization Process Flowchart for the SAS Bridge



Footnotes

[1] ASTM A143 describes procedures that can be followed to safeguard against the possible embrittlement of steel hot-dip galvanized after fabrication, and outlines test procedures for detecting embrittlement.

[2] When very high-strength steel (tensile strength higher than 150 ksi) must be galvanized, ASTM A143 suggests abrasive blasting and flash pickling, in lieu of standard pickling, to safeguard against embrittlement.

What Corrosion Protection Method Was Selected for the Rods on the SAS Bridge?

For the East Span Replacement Project, Caltrans required the bridge to have a 150-year design life, making long-term corrosion protection an important consideration. The Caltrans Bridge Design Specifications call for all ferrous bridge materials on a reinforced concrete bridge within 1,000 feet of a marine environment to be protected by hot-dip galvanizing or an equivalent protective method. Further, Caltrans Standard Special Provisions direct that high-strength fastener assemblies and other bolts attached to structural steel with nuts and washers shall be zinc-coated. For the A354 grade BD steel rods on the SAS Bridge, the T.Y. Lin International/ Moffatt & Nichol Design Joint Venture selected galvanization for long-term corrosion protection. This choice was supported by the Caltrans design oversight team. The specifics on how and why galvanization was selected compared to other methods were not documented.

Industry standards and practices cautioned about the risks associated with hot-dip galvanizing the A354 grade BD material because of susceptibility to hydrogen embrittlement, as follows:

1. The April 2000 update of the Caltrans Bridge Design Specifications Manual prohibits the galvanization of A354 grade BD rods due to hydrogen embrittlement problems.
2. ASTM A354 guidelines caution the use of hot-dip galvanizing on A354 grade BD materials, because the process could make the steel more susceptible to hydrogen embrittlement.
3. ASTM A143 provides guidance on the "Standard Practice for Safeguarding Against Hydrogen Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement."
4. General industry concern over hot-dip galvanizing of A354 grade BD rods, including suppliers that will not galvanize this type of high-strength fastener[6].

In regard to the April 2000 *Caltrans Bridge Design Specifications Manual's* restriction on galvanizing A354 grade BD rods, the design of the SAS Bridge began in early 1998 and is based on the 1995 *Caltrans Bridge Design Specifications Manual,* which was silent on the use of, and galvanizing of, A354 grade BD rods. To avoid potential design conflicts, releases of new design specifications typically are not applied mid-stream to projects already in design. As an example, the SAS Bridge contract specified the use of metric units. Newly-updated specifications required the use of English units. Updating the entire contract using English units would have been extremely costly and could have resulted in dimensional conflicts so Caltrans decided to continue design using metric units. Further, exceptions to standard bridge design specifications are allowed when necessary to meet project-specific needs. For these reasons, updates to the *Caltrans Bridge Design Specifications Manual,* released after design started, were not retroactively applied to the East Span Replacement Project.

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

[6] See website notices and cautions from Portland Bolt & Manufacturing Company and American Galvanizers Association.

Further, ASTM A143 on "Standard Practice for Safeguarding Against Hydrogen Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement" suggests the elimination of pickling — a pre-galvanizing cleaning process — may reduce the risk of hydrogen embrittlement when galvanizing. For example, on the Golden Gate Bridge Seismic Retrofit, pickling was explicitly eliminated for A354 grade BD rods even though those rods were not to be galvanized.

Correspondence between Caltrans and the T.Y. Lin International/Moffatt & Nichol Design Joint Venture in 2003 indicates that both parties were aware of the challenges with hot-dip galvanizing the A354 grade BD rods and the potential for hydrogen embrittlement. To avoid the problem, the initial specifications for the SAS Bridge contracts required the rods to be mechanically galvanized — a method of galvanizing that would subject the rods to less heat and less potential for hydrogen embrittlement — versus hot-dip galvanizing. However, a bidder inquiry at the time of advertisement of the East Pier/Tower (E2/T1) Marine Foundation Contract noted an inability to mechanically galvanize the large 3-inch and 4-inch diameter tower anchor rods. After further investigation, the general conclusion among both T.Y. Lin International/ Moffatt & Nichol Design Joint Venture and Caltrans design staff was that the tower rods were too long and too heavy for the mechanical process.

In March 2003, SAS design staff learned that the Richmond-San Rafael Bridge Seismic Retrofit Project also included A354 grade BD rods that were galvanized for corrosion protection. The Richmond-San Rafael Bridge Seismic Retrofit Project had changed its requirement for mechanical galvanizing of A354 grade BD rods to hot-dip galvanizing (because of the size of the rods), with an explicit instruction to use dry blast cleaning in lieu of cleaning in a pickling solution prior to galvanizing. The rods on the Richmond-San Rafael Bridge project were installed, in many locations underwater, to a low-tension snug-tight fit, without any apparent problems. Based on Caltrans' experience on the Richmond-San Rafael Bridge, and by adding a requirement that certified test results be submitted for conformance to ASTM A143, the SAS Bridge design team and the Caltrans design oversight team appeared reassured that hot-dip galvanizing could be performed successfully while avoiding hydrogen embrittlement by requiring dry blast cleaning in lieu of pickling for the A354 grade BD high-strength rods. This led to the issuance of Addendum #3 to the E2/T1 Marine Foundation Contract in April 2003, which included these requirements.

There is little documented discussion regarding the variety of applications and far higher tension levels that would be placed on some of the high-strength rods on the SAS Bridge and potential alternative corrosion protection methods.

Table 5 presents the timeline of major design and contract milestones for the Bay Bridge East Span replacement project related to the use of A354 grade BD galvanized high-strength rods. These major milestones also are depicted in the timeline in Figure 16.

Table 5 Major Design and Contract Decision Timeline

Date	Event
August 1994	The Caltrans Bridge Design Specification Manual is updated. In this new 1995 Caltrans Bridge Design Specification Manual and in all previous releases, "Section 10 - Structural Steel," does not address the use of A354 grade BD high-strength rods.
January 1998	The T.Y. Lin International/Moffatt & Nichol Design Joint Venture, the Engineer of Record for the SAS Bridge, begins design of the bridge using design standards in effect at the time, including the 1995 Caltrans Bridge Design Specification Manual.
August 1999	Caltrans advertises the Richmond-San Rafael Bridge Seismic Retrofit Project with contract specifications that include A354 grade BD galvanized rods. Per this project's Special Provisions Section 10-1A.27 STEEL CASINGS, "High-strength threaded rods and rods for steel casings shall conform to ASTM Designation A354 grade BD and shall be installed snug-tight in 3/16-inch oversized holes. High-strength rod assemblies shall be galvanized using a mechanically-deposited zinc coating conforming to ASTM B695, Class 50." By mechanically galvanizing, the rods would be subjected to less heat and thereby reduce risks for hydrogen contamination and embrittlement.
April 2000	The Caltrans Bridge Design Specification Manual is updated. Additional structural fasteners are added to the specifications as a design choice, including A354 high-strength fasteners (Section 10.2.4 and Table 10.2C). Section 10.24.1.1 adds, "Galvanization of AASHTO M253 (ASTM A490) and A354 grade BD high-strength bolts is not permitted due to hydrogen embrittlement problems. These fasteners must be carefully evaluated before being utilized."[7,8]
August 2001	Caltrans issues Contract Change Order (CCO) #53 on the Richmond-San Rafael Bridge Seismic Retrofit Project that changes the galvanizing of A354 grade BD rods from mechanical galvanization to hot-dip galvanization, as the size of the rods specified were too large to be mechanically galvanized. The CCO also contained the following language: "In lieu of cleaning of the high-strength rod assemblies in pickling solution prior to galvanizing, all surfaces of the assemblies shall be dry blast cleaned in accordance with provisions of Surface Preparation Specification No. 10, "Near White Blast Cleaning," of Steel Structures Painting Council. The assemblies shall be coated with galvanizing within 4 hours of being dry blast cleaned." This contract change is consistent with ASTM A143 (Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement) that specifies that abrasive blast cleaning, followed by flash pickling, may be employed when very high-strength steel (ultimate tensile strength higher than 150 ksi) is galvanized.

table continued

[7] Caltrans Bridge Design Specifications (February 2004). "Section 10-Structural Steel," p. 10-39.

[8] Memo from Steel Committee Chair (Lian Duan) to Caltrans (Ade Akinsanya) (January 2003). "Review Comments on SFOBB-East Span Seismic Safety Project Self-Anchored Suspension Bridge."

[9] Letter from T.Y. Lin International/Moffatt & Nichol Design Joint Venture in Response to Memo from Steel Committee Chair (January 2003).

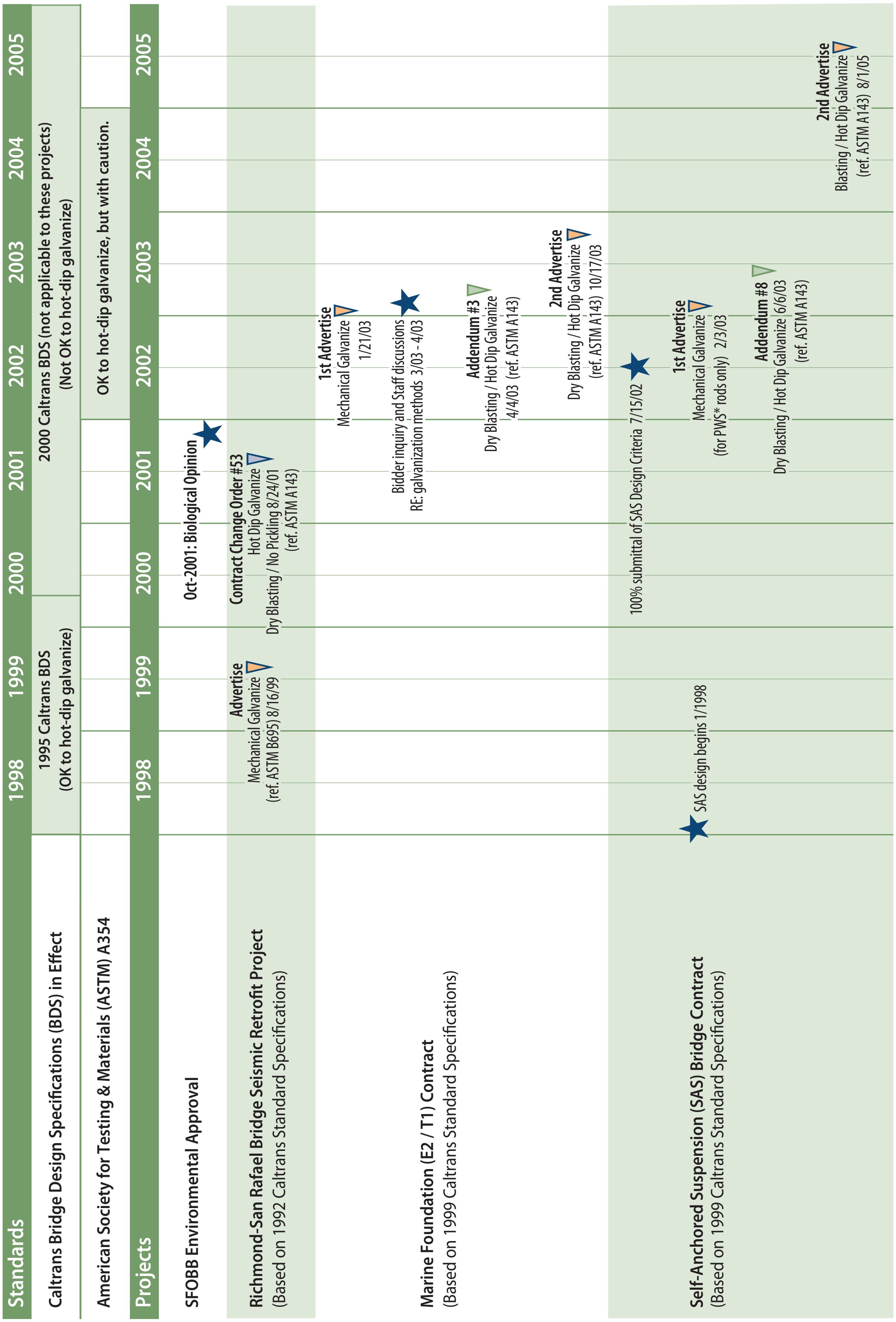
Table 5 Major Design and Contract Decision Timeline (continued)

Date	Event
September 2001	The T.Y. Lin international/Moffatt & Nichol Design Joint Venture requests approval from Toll Program to seek limited sole-source approval for one particular location. Request communicates lack of availability of domestic 3-inch high-strength rods at the time and communicates intent to use A354 grade BD rods on other portions of the SAS bridge. There is no mention of corrosion protection.[9]
July 2002	The T.Y. Lin international/Moffatt & Nichol Design Joint Venture delivers the 100% submittal of the plans, specifications, estimate (PS&E) and the finalized project-specific Design Criteria for the SAS Bridge. The Design Criteria cite that the bridge shall be designed in accordance with "1995 Caltrans Bridge Design Specifications Manual" and modified and augmented as detailed in the design criteria. The criteria also cite a number of other standards and codes from American Association of State Highway and Transportation Officials (AASHTO), American Institute of Steel Construction (AISC), American Welding Society (AWS), and other technical reports. Section 6 of the Design Criteria covers structural steel and identifies ASTM A354 grade BD for use on a number of structural steel connections on the bridge, including the Pier E2 Bearing and Shear Key high-strength steel rods. The criteria do not address galvanizing or other corrosion protection for the connections.
January 2003	Caltrans Structural Steel Technical Committee provides comments to Toll Program on 100% submittal of the PS&E package for the SAS Bridge. Comments request "corrosion resistance specifications for A354 fasteners." Caltrans advertises the Pier E2/Tower T1 (E2/T1) SAS Marine Foundation Contract that includes requirements for mechanically galvanized A354 grade BD high-strength steel rods similar to the A354 grade BD provisions specified in the original August 1999 advertisement of the Richmond-San Rafael Bridge Seismic Retrofit Project.
February 2003	Caltrans advertises the SAS Bridge Contract that includes requirements for A354 grade BD Parallel Wire Strand (PWS) anchor rods, and requirements that these rods be mechanically galvanized, similar to the provisions identified in the August 1999 advertisement of the Richmond-San Rafael Bridge Seismic Retrofit Project. Galvanization of other A354 grade BD rods on the SAS was not addressed. The T.Y. Lin international/Moffatt & Nichol Design Joint Venture responds to January 10, 2003 comments from the Caltrans Structural Steel Technical Committee.[10] Response discusses concern about hydrogen embrittlement and continuing discussion about corrosion protection.

[10] *Ibid.*

Date	Event
March 2003	Caltrans receives a bidder inquiry on the E2/T1 Marine Foundation Contract stating that high-strength steel rods cannot be mechanically galvanized due to their size; bidder inquires about how to coat the rods.
March 2003 to April 2003	In response to the bidder inquiry, staffs from Caltrans and the T.Y. Lin International/ Moffatt & Nichol Design Joint Venture discussed the need to modify galvanizing specifications for A354 grade BD rods. They explored the Richmond-San Rafael Bridge Seismic Retrofit Project change order (CCO #53) for use of dry blast cleaning prior to hot-dip galvanizing as a response to the inquiry. Caltrans staff raised concerns about "strain age embrittlement" and suggested adding specification language for the contractor to follow ASTM A143. Both Caltrans and T.Y. Lin International/Moffatt & Nichol Design Joint Venture staffs conclude that adding the changes implemented on the Richmond-San Rafael Bridge Seismic Retrofit Project, including blasting and tensile testing, would allow for successful galvanizing while reducing the risk for hydrogen embrittlement.
April 2003	Caltrans issues Addendum #3 to the E2/T1 Marine Foundation Contract requiring that the A354 grade BD rods be dry blast cleaned 4 hours prior to hot-dip galvanizing and that the contractor submit certified test reports that the rods conform to ASTM A143.
June 2003	Caltrans issues Addendum #8 to the SAS Bridge Contract requiring that all A354 grade BD rods be dry blast cleaned 4 hours prior to hot-dip galvanizing, and that the Contractor submit certified test reports that the rods conform to ASTM A143.
October 2003	Caltrans rejects the single bid received on the E2/T1 Marine Foundations Contract as unacceptably high. Note: when Caltrans awards the contract in April 2004, the new bid is $50 million lower than the earlier bid. Caltrans re-advertises the E2/T1 Marine Foundations Contract with the special provisions to dry blast clean A354 grade BD rods 4 hours prior to hot-dip galvanizing and to conform to ASTM A143.
September 2004	Caltrans receives a single bid for the SAS Bridge Contract in May 2004. The sole bid came in at $1.8 billion (in contrast to the engineer's estimate it would cost $733 million). Caltrans did not accept the single bid. Instead, Caltrans stated it would further analyze whether to resubmit the original SAS design in an attempt to attract more bids, or possibly reopen the design process to find a less expensive design.
August 2005	Caltrans re-advertises the SAS Bridge Contract with special provisions included to dry blast clean A354 grade BD rods 4 hours prior to hot-dip galvanizing and to conform to ASTM A143.

Figure 16 Timeline of Major Design and Contract Milestones



Fabrication

What Are Standard Industry Practices for Fabricating A354 Grade BD Rods? Were They Followed?

The American Society for Testing and Materials (ASTM) is one of the largest organizations in the world for the development of voluntary consensus standards for test methods and material specifications. There are more than 12,000 ASTM standards today. Many users refer to them for guidance, as ASTM standards are voluntary. However, government regulators often give these voluntary standards the force of law by citing them in contract laws, regulations and codes. The ASTM standards relevant to the fabrication process for the type of high-strength steel rods that are the subject of this report are summarized in Table 6.

Table 6 Summary of Relevant ASTM Standards

ASTM	Title	Relevance to the SAS Bridge Project
A123	Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products	ASTM A123 describes hot-dip galvanizing specifications for steel.
A143	Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement	ASTM A143 describes procedures that can be followed to safeguard against, as well as to test for, possible embrittlement of steel that has undergone a hot-dip galvanization process, as was the case for the A354 grade BD high-strength steel rods for this project. ASTM A143 identifies an alternative test for hydrogen embrittlement, as described in ASTM F606. When very high-strength steel (tensile strength higher than 150 ksi) must be galvanized, ASTM A143 suggests abrasive blasting and flash pickling, in lieu of standard pickling, to safeguard against embrittlement.
A354	Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs and Other Externally Threaded Fasteners	Where high-strength steel is required for threaded rods of no more than 4 inches in diameter, as in the case of this project, ASTM A354 specifies the chemical composition required to qualify the steel as an alloy steel. ASTM A354 also specifies the required mechanical properties, in terms of hardness and tensile strength, for various diameter rod sizes. ASTM A354 identifies the type of test methods that shall be used to ensure the mechanical properties of the rods are met. ASTM A354 specifies requirements for the hot-dip galvanizing process, as described in ASTM F606, but cautions hot-dip galvanizing A354 steel by stating, "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." The A354 rods that are the subject of this report were hot-dip galvanized. A354 grade BC steel rods: Minimum tensile strength = 125 ksi (¼-inch to 2½-inch diameter) and 115 ksi (2¾-inch to 4-inch diameter). A354 grade BD steel rods: Minimum tensile strength = 150 ksi (¼-inch to 2½-inch diameter) and 140 ksi (2¾-inch to 4-inch diameter).

table continued on next page

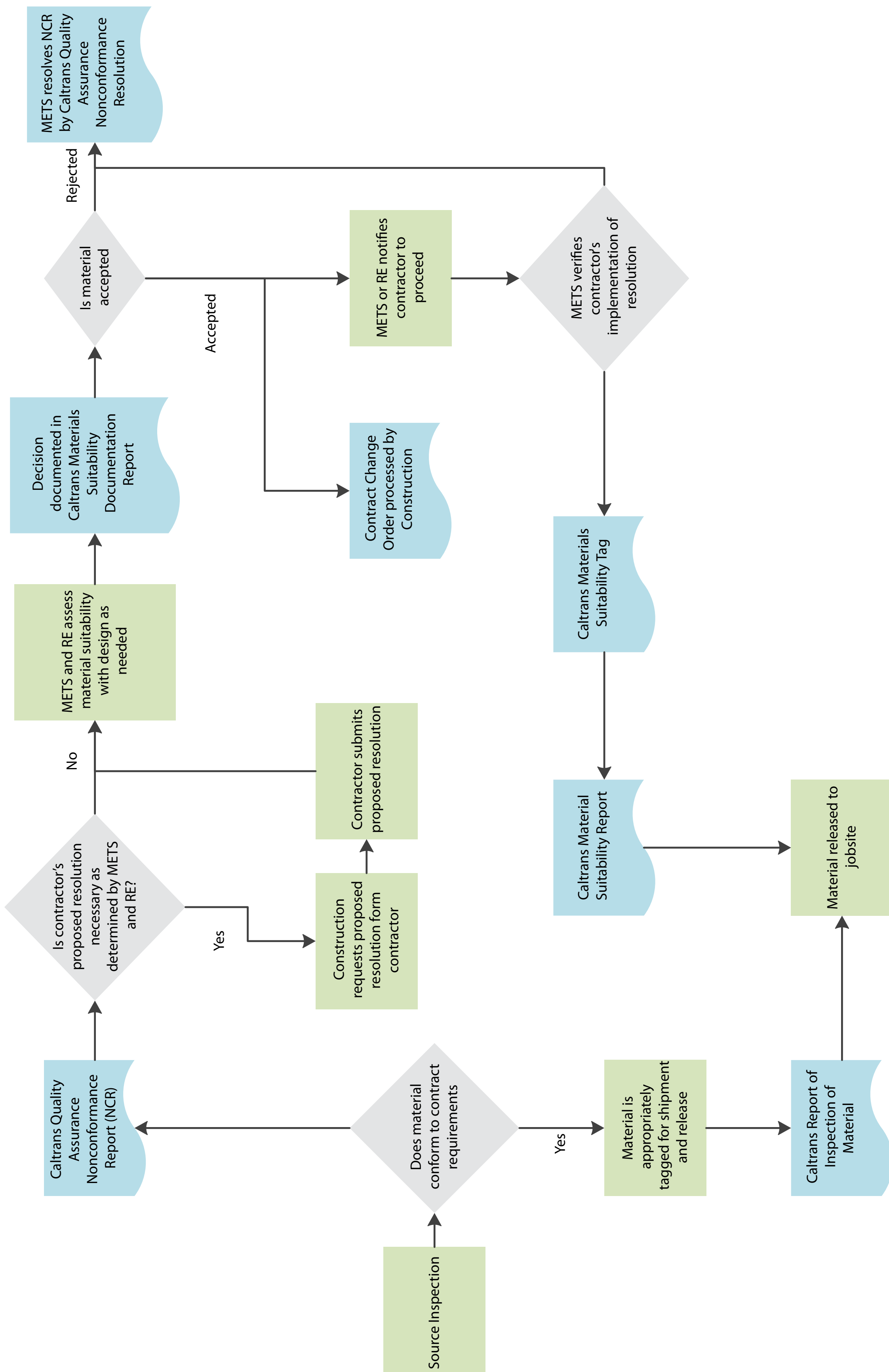
Table 6 Summary of Relevant ASTM Standards (continued)

ASTM	Title	Relevance to the SAS Bridge Project
A490	Standard Specification for Structural Bolts, Alloy Steel, Heat Treated, 150 ksi Minimum Tensile Strength	For heavy hexagon headed structural bolts ½-inch to 1½-inch diameter, ASTM A490 specifies the chemical composition and mechanical properties of the steel. This specification also specifies acceptable metallic coatings for corrosion protection, and states that no other metallic coatings, such as hot-dip zinc coating, are permitted unless authorized by the ASTM Committee F16 on Fasteners.
F606	Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets	ASTM F606 establishes the procedures for conducting tests to determine whether the mechanical properties (i.e., hardness and tensile strength) of the A354 grade BD high-strength steel rods are within the values identified in the ASTM A354 specifications. ASTM F606 identifies a test method for detecting hydrogen embrittlement, whereby a rod is installed to a fixture, with a wedge of varying angles depending on the diameter size. The rod is tensioned to measure the tensile load. ASTM F606 indicates wedge tests for rods up to 1½ inches in diameter (e.g., for diameters over ¾ to 1½ inches, a zero-angle wedge test is to be conducted). There is no reference to diameters over 1½ inches, which would cover most of the A354 grade BD high-strength steel rods for this project.
F1470	Standard Practice for Fastener Sampling for Specified Mechanical Properties and Performance Inspection	ASTM F1470 describes the number of tests to be taken per sampling of total production lot.

Inspection and Quality Control/Quality Assurance (QC/QA) General Process

As per standard industry practice and adopted throughout the East Span Replacement Project, the contractor is responsible for performing quality control (QC) inspections, which include audits of its sub-suppliers, inspection of the materials being manufactured and final inspection prior to dispatch/acceptance at site. Caltrans is responsible for performing quality assurance (QA) audits of the contractor's QC procedures and verification through sample inspection and testing of the materials and work being procured. The contractor's QC is expected to comply with the inspection and testing requirements of the contract documents, while Caltrans' QA meets the requirements of the Caltrans Office of Structural Materials (OSM) as deemed necessary by Caltrans Construction and the OSM Senior Materials Representative to provide assurance of the QC program. Figure 17 depicts Caltrans' standard QA process.

Figure 17 Caltrans QA Process — NCR and NPR Process



The contractor for the rods on the SAS Superstructure (Items #1 through #11 and #14 through #17 in Table 1) was the American Bridge/Fluor Joint Venture. The contractor for the rods on the E2/T1 Marine Foundation (Items #12 and #13 in Table 1) was the Kiewit/FCI/Manson Joint Venture.

Issues that arise during QA inspection are incorporated into a formal issue resolution process including:

- Requests for Information (RFI) - RFIs are formal requests from the contractor for additional information or clarification regarding the design and construction of the project that may be initiated by anyone associated with the project. An RFI is not a request to change the design; it is only to clarify features or the intentions for the existing design. A response to an RFI that changes the design may require the issuance of a contract change order (CCO).

- Non-Conformance Reports (NCR) - A QA inspector identifies processes or materials that do not meet contract requirements, and the contractor's QC personnel accept the material as evidence of non-conformance in the contractor's QC process. As a result, the QA inspector will write an NCR for the material, if the contractor cannot correct the deficiency within a work shift. (The QA inspector will not typically write an NCR on a material that will be corrected within a work shift and the non-conformance is not repeated, and also on material that has not been inspected and accepted by the contractor's QC personnel).

- Notice of Potential Resolutions (NPR) - Once non-conformance issues are identified and reported, the contractor's disposition and corrective action to bring the condition back into conformance will be evaluated by the Caltrans Resident Engineer (RE). Potential resolutions to non-conformance issues include:

    - Rework to meet the originally specified requirements.

    - Repair to achieve fit-for-purpose.

    - Accept the conditions as-is (may require a CCO).

    - Reject the condition by removing it and replacing it with material meeting the specified requirements.

    - Alternative fit-for-purpose evaluation - This process will allow QA inspectors to release the material when the Caltrans RE determines that the material is suitable for its intended purpose on the project. The fit-for-purpose may be initiated by NCRs, RFIs, submittals, shop drawings, contractor requests, observations, meetings or other forms of revisions.

    - Addressed the non-conformance in the contractor's QC process.

What Were the QC/QA Inspection Results for the Failed 2008 Rods?

All NCRs and NPRs issued for this project by QA were satisfactorily closed out and the 2008 rods (Item #1 in Table 1) were accepted by both the American Bridge/Fluor Joint Venture and Caltrans.

Testing on the 2008 rods was performed to contract specifications and ASTM A354 grade BD requirements. In general, the testing results during fabrication were within specification, except for low elongation results for two of the seven rod heats, which were reported in Non-Conformance Report (NCR 000199, DYSN 0005) and accepted as "fit-for-purpose" by Caltrans on October 16, 2008. Table 7 summarizes the average material test results for the 2008 rods.

Table 7 QC/QA Inspection Results of 2008 Rods

	Tensile (KSI)	Yield (KSI)	Elongation (%)	Reduction of Area (ROA)	Hardness (HRC)
ASTM A354 BD Standard	140 (Minimum)	115 (Minimum)	14 (Minimum)	40 (Minimum)	31-39 (Range)
2008 Rod Average	164	142	14.3	48.4	36.8
2008 Rod Min/Max	152/173	127/158	12.5/16.2	40/50	33/37

International and national standards, such as those issued by ASTM, provide advice to both the purchaser and the supplier. These standards are not project-specific and often require the purchaser's designer and QA to include additional or supplementary parameters to ensure that project-specific performance requirements are achieved. The supplier may also apply additional or supplementary parameters to suit its means and methods, both of which should be captured in the respective Quality Plans.

QA also noted that the 2008 rods were subjected to a second heat treatment, as the documentation for the first treatment could not be produced by the fabricator. It is not uncommon to perform a second heat treatment. However, in this case, given what is now known about the poor quality of the 2008 rod material, the second heat treatment may have further hardened and strengthened the material and contributed to the rods' susceptibility to hydrogen embrittlement.

The 2008 A354 grade BD rods used at Pier E2 were reported to have strength and hardness well above the minimum requirements of the specification. Also, when examined, the failed rods showed that the metallurgical structure was not uniform across the thickness of the rod and parts did not have the expected material properties. This indicates the steel production and heat treatment were not fully successful in achieving the desired uniform metallurgical structure and desired material properties.

Purpose of Heat Treatment

The heat treatment process is a method by which material properties are altered to suit the intended service. For these particular high-strength rods, the steel produced to American Iron Steel Institute (AISI) 4140 is sufficiently malleable for the steel rolling process to form rods from the cast ingots. Once the rods have been formed, they are subjected to a three-stage heat treatment process: austenitizing, quenching and tempering.

- The austenitizing is achieved by elevating the temperature to about 1600 degrees F, which changes the metallurgical structure.
- The quenching operation is a rapid cooling of the steel from the austenitizing temperature, causing a further change to the metallurgical structure. This increases strength, but renders the material too hard and brittle for use in rod applications.
- The tempering operation is a further elevation of the temperature to above 800 degrees F, which reduces the hardness to yield a suitable ductile/tough material (less brittle).

AISI 4140 alloy steel is a chromium-molybdenum (41) low alloy steel with approximately 0.4% (40) carbon. When properly heat treated, it can achieve high tensile strength properties. It is a commonly used alloy in bridge applications in the manufacturing of high strength rods such as ASTM F1554, A320 Grade L7, A193 Grade B7, A490 and A354 Grade BD.

Hardness

Hardness is a measure of a material's ability to resist abrasion and indentation. As a rule, an increase in the tensile strength of steel will correspondingly increase the hardness of the steel, and as explained elsewhere in this report it also increases the steel's susceptibility to hydrogen embrittlement and stress corrosion cracking.

ASTM A354 grade BD specifies an acceptance hardness range for high-strength rods of between 31 HRC and 39 HRC. In 2005, revisions to ASTM F2329 included the risk of embrittlement for high-strength rods 33 HRC and above, recommends measures to reduce such risks. The consensus of experts, including John W. Fisher and H.E. Townsend, is that the acceptable range of hardness for high-strength rods with appropriate fabrication control measures is 31 HRC to 35 HRC.

Hardness testing specified by ASTM on rods and bolts requires measurements to be taken at location mid-radius, or R/2, (mid-point between the rod center and the circumference/rod surface). QC and QA testing of high-strength rods per the SAS contract were performed in accordance with ASTM F606 with hardness measurements taken at R/2.

Construction

How Did Environmental Conditions at the Construction Site Affect A354 Grade BD Rods?

The rods installed at Pier E2 were manufactured by Dyson in Ohio in 2008, and were installed prior to the final concrete pour on December 5, 2008. These high-strength steel rods were embedded within the pier directly above the columns, and were sitting in ducts for five years before they were tensioned. During this five-year period, water was pumped out of the ducts a number of times at the request of Caltrans. Temporary drainage and sealing arrangements had not prevented the ingress and collection of rainwater, since it had not been anticipated that there would be such an extended period prior to completing the erection and grouting operation at Pier E2. The actual length of time during which water was present in these holes is unknown, but the presence of water may have been a contributing source of hydrogen contamination in the rods (see photo in Figure 18).

Figure 18 Pier E2 Cap Construction Photograph — Embedded rods are in holes

Was the 2008 Rod Order Rushed? Did This Have an Effect on the Quality?

In the QA/QC records, it was noted that the 2008 rods were shipped from the fabricator to the project site prior to completion of laboratory QA testing. American Bridge/Fluor Joint Venture took the risk of shipment without full testing results in order to meet their construction schedule for completion of Pier E2. Nonetheless, the 2008 rods were not installed into place until all required tests were completed and passed. There is no evidence that this sequence of events led to the rod failures.

5. Question 2: What Retrofit Strategy Should Be Used to Replace the Lost Clamping Force of the 2008 Rods at Pier E2?

Are the Failed 2008 A354 Grade BD Rods Replaceable?

The 2008 A354 grade BD rods installed in Pier E2 cannot be replaced. These rods were installed and embedded into the Pier E2 cap, and are in-line with the vertical columns of the pier. In addition, the OBGs have been placed over the shear keys, further limiting access to the rods. Therefore, replacing these 96 rods would require significant destruction of the pier cap to allow for the removal of the 2008 rods and installation of replacement rods. Thus, the lost clamping force from the failure of the 2008 rods must be replaced in another fashion.

What Retrofit Strategies Were Considered?

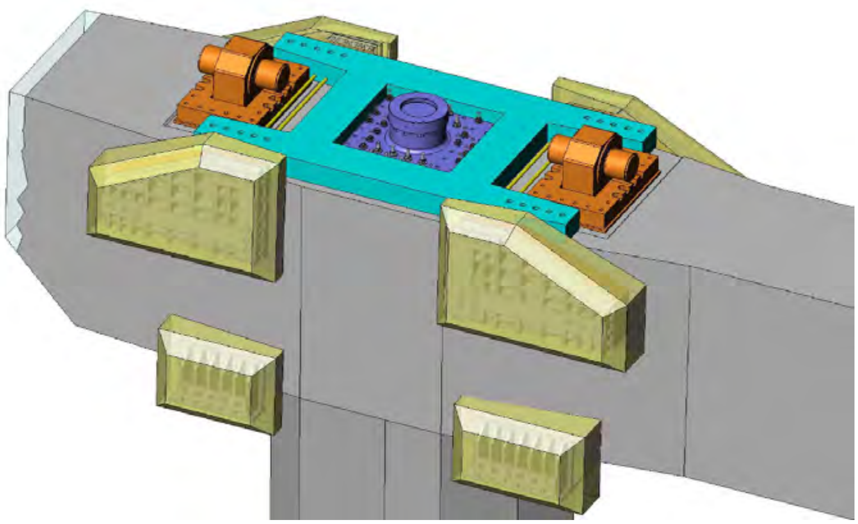
Upon discovering the fractured rods, Caltrans, the T.Y. Lin International/Moffatt & Nichol Design Joint Venture and the American Bridge/Fluor Joint Venture began to consider a retrofit strategy in lieu of replacement. Replacing the failed rods with a similar anchoring system was not a practical solution. The design constraints included:

- The rods could not simply be removed due to the original embedded design. The embedded end of the rod was permanently secured by deforming the thread to prevent the rod from unscrewing from the nut.
- The vertical clearance between the bottom of the roadway boxes and top of pier cap is far less than the 17 feet length of the rods. Also, with the bearings installed adjacent to the shear keys, the horizontal clearance is likewise limited.
- There is an extensive amount of steel reinforcement in the concrete pier cap, thus making modifications to accommodate a new anchor rod system in the pier cap challenging.
- High clamping force is still required to maintain the seismic design requirements.

Three potential alternatives were considered by the TBPOC for the retrofit of the lower housing of shear keys S1 and S2. These alternatives included: (1) a steel collar that captures the perimeter of the lower shear key housing and is anchored to the pier cap using through post-tensioning tendons; (2) a steel saddle that extends over the lower housing of the shear key with post-tensioning that extend over the sides of the cap; and (3) removal and replacement of the existing anchor rods with new coupled anchor rods that would have a bonded zone in the pier cap. These three options are described in more detail below.

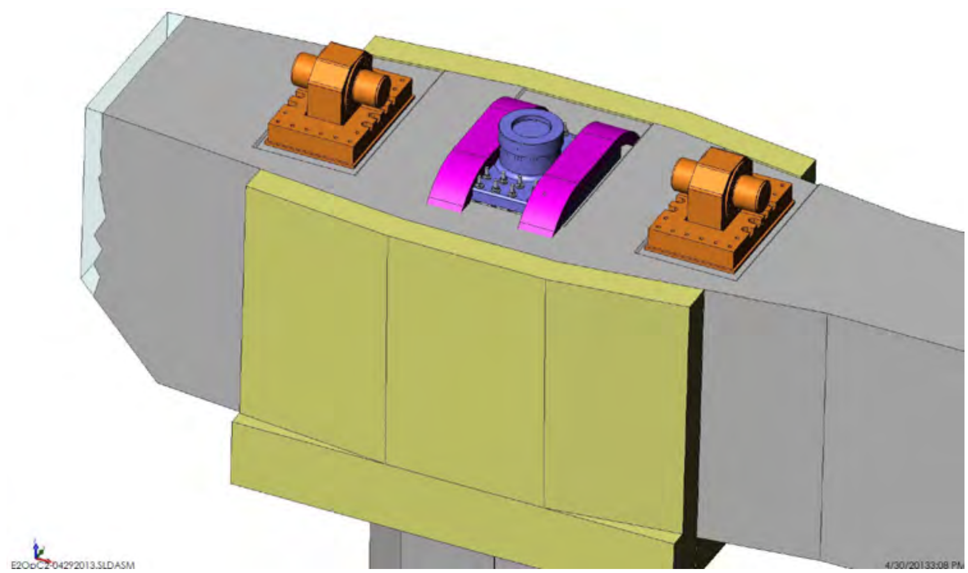
Option 1: Steel Collar (Figure 19) — This option secures the perimeter of the lower shear key housing with a steel brace that is anchored to the pier cap with anchor rods. The new anchor rods would be installed through cored holes in the pier cap on either side of the column.

Figure 19 Early Rendering of Option 1 — Steel Collar



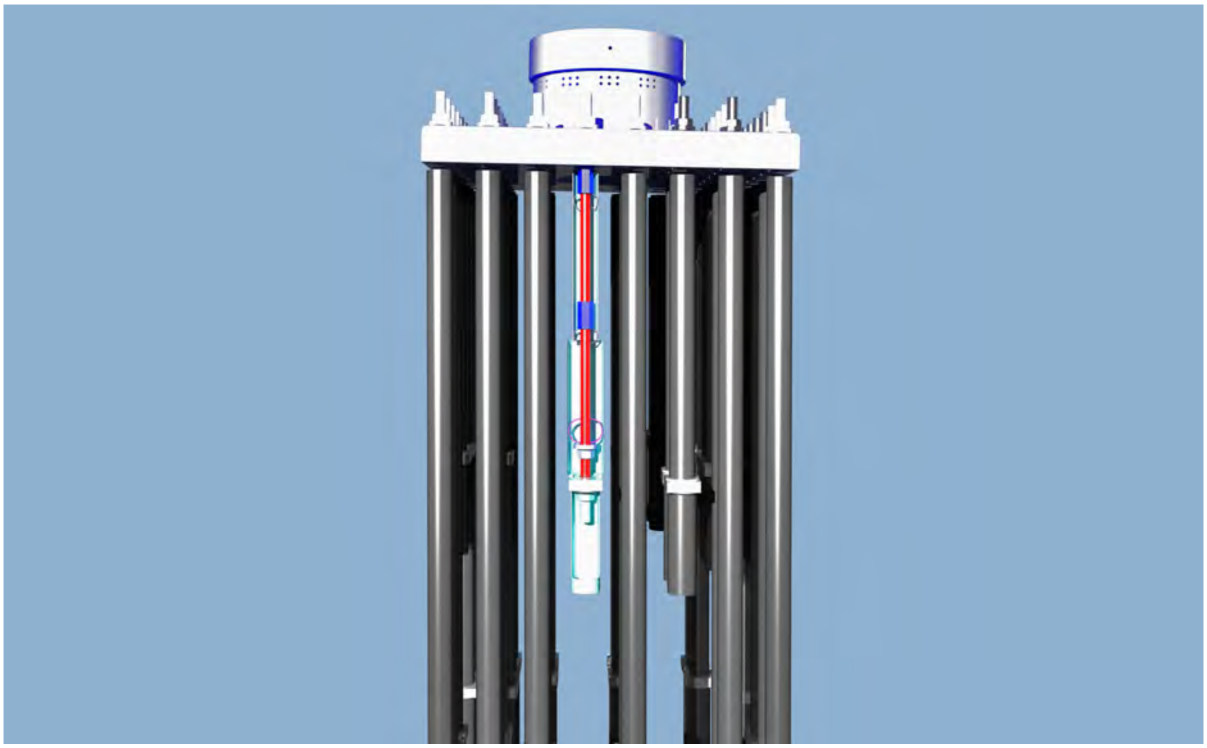
Option 2: Steel Saddle (Figure 20) — This option would secure the lower housing of the shear key with post-tensioning cables that extend over the sides of the cap. The cables would then be encased in a concrete blister outside of the pier cap, minimizing the impact to the cap.

Figure 20 Early Rendering of Option 2 — Steel Saddle



Option 3: Post-Tension Tie Down (Figure 21) — This option explored the removal of the shear keys so that all the broken and unbroken rods could be replaced with post-tensioning cable anchors. Conceptually, this would require the removal of the unbroken rods, the broken rod remnants and grout with high-precision water jets from the anchorage ducts in Pier E2, and development of a post-tension anchor system for installation at the bottom of the 17-foot-deep ducts.

Figure 21 Early Rendering of Option 3 – Post-Tension Tie Down



In all cases, the 2008 A354 grade BD rods would be completely abandoned and replaced with equivalent clamping capacity.

Which Retrofit Strategy Option Was Selected by the TBPOC and Why?

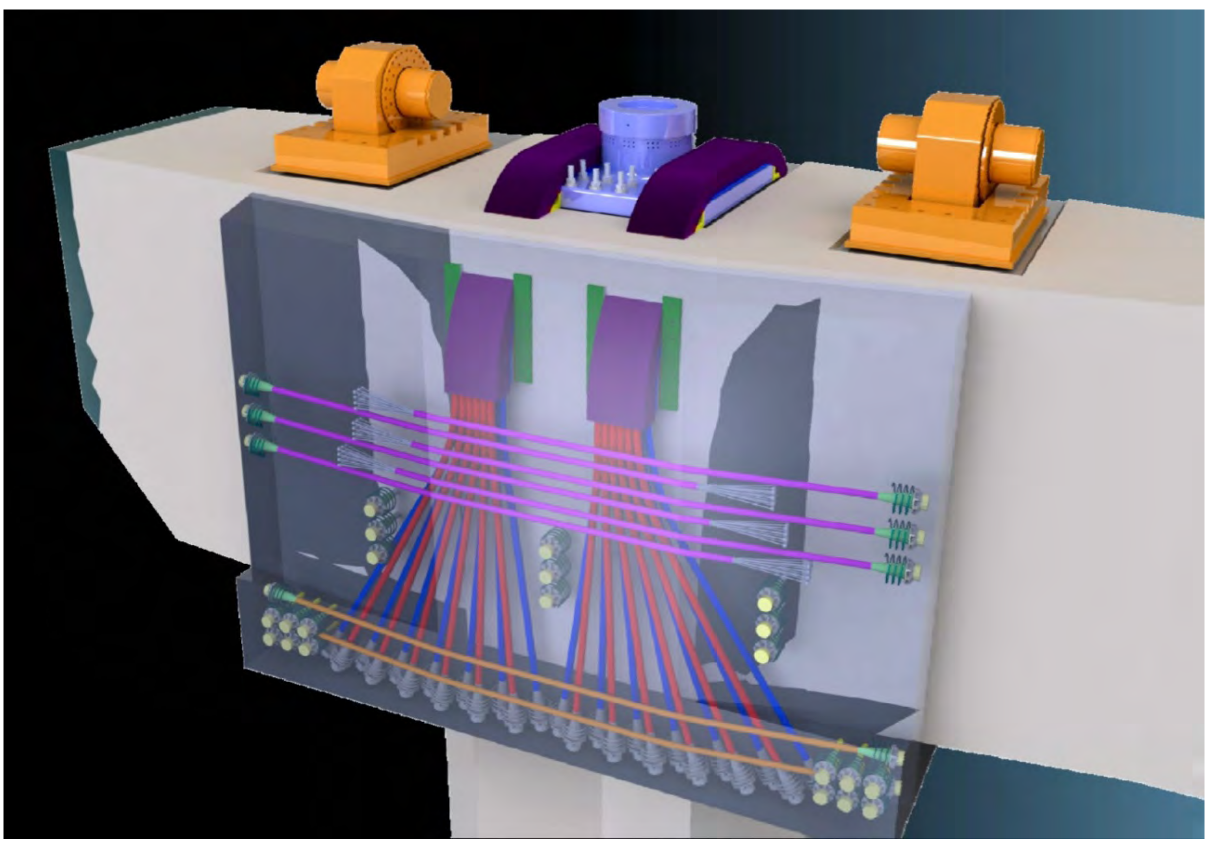
On May 8, 2013, the Toll Bridge Program Oversight Committee (TBPOC) evaluated three options that were presented by Caltrans bridge designers and then directed attention to two options: Option 1 (Steel Collar) and Option 2 (Steel Saddle). Both options and their pros and cons are shown in Table 8. Note that both options would provide equivalent clamping force as the original anchor rod design to secure the shear keys and resist the significant forces of a seismic event. Both options would completely abandon the 2008 A354 grade BD rods. Option 3 was eliminated from further consideration because the other options had fewer design and construction challenges, including no removal and reinstallation of the shear keys and no use of high-precision water jets within close proximity to the structural reinforcement tendons.

Table 8 General Comparison of Retrofit Options for 2008 High-Strength Steel Rods

Option 1: Steel Collar	Option 2: Steel Saddle
Pros: No need to remove shear keys S1 and S2 Potentially simpler to fabricate	**Pros:** No need to remove shear keys S1 and S2 Less coring of E2 required Potentially less difficult to install Less costly: $10 million
Cons: Need to find sufficient materials and resources More coring of E2 required More costly: $15 to $20 million	**Cons:** Requires unique saddle system

Option 2 (Steel Saddle) was the selected retrofit strategy option because it was considered to be easier to construct and less expensive. As shown in Figure 22, it also applies a direct preload to the lower housing via the radial forces that are developed from the main vertical post-tensioning force being applied as intended in the original design. The project's Seismic Peer Review Panel also supported this option, and the American Bridge/Fluor Joint Venture indicated this option would be the easiest to construct and the fastest option to complete. On May 8, 2013, the TBPOC unanimously approved selection of the steel saddle retrofit (Option 2) after finding that it would meet all design requirements and objectives of the project.

Figure 22 Recent Rendering of Selected Steel Saddle Option



6. Question 3: What Should Be Done About Other A354 Grade BD Rods on the SAS Bridge?

Where Are the A354 Grade BD Rods Located on the SAS Bridge?

The A354 grade BD rods used on the SAS Bridge are at various locations and of varying diameters, lengths and applied tension levels. The A354 grade BD galvanized rods generally can be split into three groups: 1) tower anchor rods (Items #12 and #13) fabricated and installed under the SAS Bridge Marine Foundation contract; 2) the failed 2008 lower Pier E2 shear key anchor rods (Item #1) fabricated and installed under the SAS Bridge Superstructure contract; and 3) other rods (Items #2 to #11 and #14 to #17) fabricated and installed under the SAS Bridge contract. (Refer to Table 1 and Figure 2 for the locations of these rods.)

The contract work includes installation of a desiccant dehumidifier system in the Bottom of the Tower, at the Top of the Tower and in the Main Cable Anchorage. Rods at these locations (Items #7, 8, 9, 12 and 13) have required dehumidification systems controlling their environment. This equipment will remove moisture (hydrogen) from the air.

Who Fabricated the A354 Grade BD Rods? When Were the Rods Fabricated and Tensioned?

The tower anchor rods (Items #12 and #13 in Table 1) were fabricated in early 2007 at Vulcan Threaded Products in Alabama under the SAS Bridge Marine Foundation contract. The remaining rods were fabricated by Dyson Corporation in Ohio under the SAS Bridge Superstructure contract. The Dyson rods were fabricated during two periods – in 2008 for the E2 shear keys S1 and S2 (Item #1 in Table 1) and between 2009 and 2012 for the remaining rods. Table 9 provides a summary of the fabricators and key fabrication and tensioning dates for all the high-strength steel rods.

Table 9 Fabrication Dates and Status of A354 Grade BD High-Strength Steel Rods

Item #	Fabricator	End of Fabrication	Tension or Loading Complete	# of Rods Installed	# of Fractured Rods After Tensioning	Days Under Tension Through July 1, 2013
1	Dyson	Sep 2008	Mar 2013	96	32*	Rods began failing after 3 days of tensioning
2	Dyson	Mar 2010	Apr 2013	192	0	91
3	Dyson	Mar 2010	Sep 2012	320	0	295
4	Dyson	Mar 2010	Sep 2012	224	0	292
5	Dyson	Aug 2009	Jun 2009**	96	0	1,429
6	Dyson	Dec 2009	Jan 2010	336	0	1,245
7	Dyson	Nov 2011	Sep 2012	274	0	278
8	Dyson	Jul 2010	Jul 2012	25	0	351
9	Dyson	Jan 2011	Jul 2012	108	0	351
10	Dyson	Jan 2011	Mar 2013	90	0	97
11	Dyson	Oct 2011	Jul 2012	4	0	334
12	Vulcan Threaded Products	Feb 2007	Mar 2011	388	0	821
13	Vulcan Threaded Products	Feb 2007	Mar 2011	36	0	821
14	Dyson	Jun 2010	May 2010**	32	0	1,125
15	Dyson	May 2010	Apr 2012	18	0	443
16	Dyson	Oct 2012	Feb 2013	24	0	142
17	Dyson	Jun 2009	TBD***	43	0	—

* Caltrans reduced the tension on the remaining unfractured rods on March 15, 2013. Additional rods might have fractured if not detensioned.

** Rods were tensioned in the fabrication shops, Item #5 in Japan and Item #14 in China, prior to the assembly being delivered to SAS Bridge site. Items #7, 8, 12 & 13 were adjusted as part of Load Transfer in October 2012.

*** Details for bike path support frame being redesigned to improve consistency with other design features of SAS.

What Were the Differences in Fabrication?

While all the rods were fabricated by the same general processes, there were two notable differences in fabrication procedure for certain rods:

- Under the SAS Bridge Marine Foundation contract, the tower anchor rods (Items #12 and #13) were produced by a different fabricator (Vulcan Threaded Products in Alabama) than where the remaining SAS rods were fabricated. Contract specifications for this contract required A354 Grade BD rods to be galvanized with a dry blast cleaning. While complete Caltrans QA records have not been located, contractor QC documentation for these rods provided mechanical property information beyond that normally required by Caltrans. QC documentation included microstructural analysis and a full cross-sectional hardness survey. In addition, these rods were subjected to induction heat treatment, similar to the 2010 rods but different from the 2008 rods both fabricated at Dyson. Recent documentation from the fabricator notes that the rods were dry blast cleaned and flash pickled as per specification.

- Under the SAS Bridge Superstructure Contract in October 2008, Caltrans directed American Bridge/Fluor Joint Venture, through Contract Change Order (CCO) #91, to perform additional Magnetic Particle Testing (MT) during fabrication — in accordance with ASTM specification A490 — on A354 grade BD high-strength steel rods tensioned in excess of 0.5 Fu. MT is a non-destructive method for detecting cracks and other discontinuities at or near the surface in ferromagnetic materials such metals as iron, nickel, cobalt and some of their alloys. This change was in addition to contract specifications to galvanize with a dry blast cleaning.

CCO #91 was further clarified by American Bridge/Fluor Joint Venture on May 22, 2009 in a request for information[11] to cover the rods listed below:

Item #2 - Bearing & Shear Key Anchor Rods

Item #3 - Shear Key Rods (top)

Item #4 - Bearing Rods (top)

Item #5 - Bearing Assembly

Item #7 - Parallel Wire Strand (PWS) Anchor Rods

Item #8 - Saddle Tie Rods (top of tower)

Item #15 - Saddle Tie Rods (East saddles)

Item #16 - Cable Band Anchor Rods

The 2008 rods were already galvanized and beyond the point when MT could be performed, therefore no MT was performed on the 2008 high-strength steel rods. The reason for directing the contractor to perform MT, through CCO #91, at this stage in the project is not documented.

According to American Bridge/Fluor Joint Venture and confirmed by project QC records, in response to this new requirement for MT, the American Iron and Steel Institute (AISI) 4140 steel alloy supplied by the steel manufacturer, Gerdau Long Steel, started coming from a steel mill that used the “vacuum de-gassing” process in their production. Vacuum degassing is a process where molten metal (commonly steel) is placed in a vacuum furnace in order to remove excess hydrogen or carbon. This additional process may have improved the material properties of the rods manufactured with degassing by reducing internal hydrogen trapped in the steel.

Table 10 shows the QA/QC inspection data for the high-strength rods used on the SAS with diameters greater than 2½ inches, and Table 11 shows the QA/QC inspection data for the high-strength rods used on the SAS with diameters between ¼ inch and 2½ inches.

[11] Request for Information (RFI) (RFI No. ABF-RFI-00174R01) (May 2009) regarding CCO-91 Clarification

Table 10 Post-Heat Treatment QC/QA Mechanical Test Results (> 2½-inch diameter)

Item #	Component	Average Min/Max	Tensile (ksi)	Yield (ksi)	Elongation (%)	Reduction of Area (%)	Hardness (HRC)
ASTM D>2½"			140 (min)	115 (min)	14 (min)	40 (min)	31 - 39
1	E2 Shear Key Anchor Rods	Average	164	143	14	48	36.8
		Min/Max	152/173	127/158	13/16	40/50	33/37
2	E2 Bearing & Shear Key Anchor Rods	Average	159	139	16	51	34
		Min/Max	153/165	132/147	13/17	40/55	32/37
3	E2 Shear Key Rods (top)	Average	159	141	16	46	35
		Min/Max	153/163	133/148	14/17	40/53	32/37
7	PWS Anchor Rods	Average	157	137	16	53	35
		Min/Max	145/167	121/149	14/20	48/57	31/39
8	Tower Saddle Tie Rods	Average	161	133	15	44	35
		Min/Max	154/172	123/161	14/16	41/47	32/37
9	Tower Saddle Turned Rods	Average	148	125	19	57	37
		Min/Max	145/151	121/129	17/20	57/57	36/38
10	Tower Saddle Grillage	Average	150	124	16	53	34
		Min/Max	147/153	118/127	15/17	52/54	32/34
11	Tower Outrigger Boom Anchor Rods	Average	158	135	15	48	39
		Min/Max	156/161	132/140	14/16	48/48	39/39
12	Tower Anchor Rods (Type 1)	Average	160	144	18	51	34
		Min/Max	151/167	131/153	16/21	47/53	32/35
13	Tower Anchor Rods (Type 2)	Average	154	132	16	45	33
		Min/Max	152/158	129/136	15/17	40/50	33/34
15	East Saddle Tie Rods	Average	148	121	17	53	33
		Min/Max	146/152	118/127	16/18	52/54	32/34
16	Cable Bracket Anchor Rods	Average	156	134	16	53	36
		Min/Max	154/158	129/139	15/16	52/54	32/38

Table 11 Post-Heat Treatment QC/QA Mechanical Test Results (¼-inch to 2½-inch diameter)

Item #	Component	Average Min/Max	Tensile (ksi)	Yield (ksi)	Elongation (%)	Reduction of Area (%)	Hardness (HRC)
ASTM D = ¼″–2½″			140 (min)	115 (min)	14 (min)	40 (min)	31 - 39
4	E2 Bearing Rods (top)	Average	161	135	16	54	35
		Min/Max	156/164	126/151**	15/17	53/55	32/37
5	E2 Bearing Assembly Bolts	Average	166	154	18	56	36
		Min/Max	161/174	146/162	17/20	53/60	33/37
6	Retaining Ring Bearing Assembly Bolts	Average	166	148	15.8	50	35
		Min/Max	157/176	130/163	15/17	46/54	32/37
14	East Saddle Anchor Rods	Average	156	137	15	55	37
		Min/Max	154/160	132/142	14/16	55/55	37/37
17	Bikepath Anchor Rods	Average	167	160	15	52	36
		Min/Max	160/179	150/171	15/15	52/52	35/37

*All mechanical property tests including elongation are the result of averaged data from two samples from each heat. If one sample is below specification and the second is above, with the average then being above specification, the test is passed. The minimums and maximums above reflect individual sample minimums and

**Samples from Heat # NSH2 were rejected by CALTRANS TRANSLAB for low yield values. The lot was resampled & retested with satisfactory results.

Is There Still a Risk of Hydrogen Embrittlement on the 192 Other Pier E2 A354 Grade BD Rods?

Following the 2008 rod failures, a test protocol was established for testing the 192 rods located on the east pier that were manufactured in 2010 (Item #2 in Table 1). Aside from the bike path anchor rods (Item #17), these A354 grade BD rods were the last remaining to be tensioned. The basis of the procedure was to perform a monitored, time-dependent, *in-situ* tensioning test on all remaining 192 rods to determine their susceptibility to hydrogen embrittlement. This tensioning test was conducted over a period of 30 days, which was considered sufficient time to ascertain whether 'internal' hydrogen was likely to embrittle the rods. Tensioning of the 192 rods was completed on April 9, 2013, at which time the 30-day *in-situ* test period began. The 30-day *in-situ* test period was completed on May 9, 2013, and resulted in no rod failures or evidence of hydrogen embrittlement. As of July 1, 2013, these rods continued to perform as designed.

A number of rods were extracted and subjected to an extended test program to determine if hydrogen embrittlement had occurred. These extracted rods were examined extensively and no evidence of hydrogen embrittlement was found. Further the 2010 material properties were substantially better than the 2008 material with homogenous microstructure and improved toughness. The 2008 material failed at a tension level substantially lower than the actual yield strength of the rods, which is evidence of hydrogen embrittlement and lack of toughness. Laboratory testing results for both the 2008 and 2010 rod results are shown in Table 12 and Figure 23.

The 2010 pier cap rods on Pier E2 exhibited substantially higher toughness values — at 40 degrees F — between 36.6 to 38.3 ft-lbs as compared to 13.5 to 17.5 ft-lbs for the 2008 rods. The hardness profiles for the 2010 rods also are somewhat more uniform through the rods as compared to the 2008 rods. Given these material differences in the 2010 rods and the elapsed time since they were tensioned, the near-term risk of further hydrogen embrittlement in the rods on Pier E2 is low.

Table 12 Mechanical Test Comparison 2008 vs. 2010

1. Reduced Section Tensile Testing

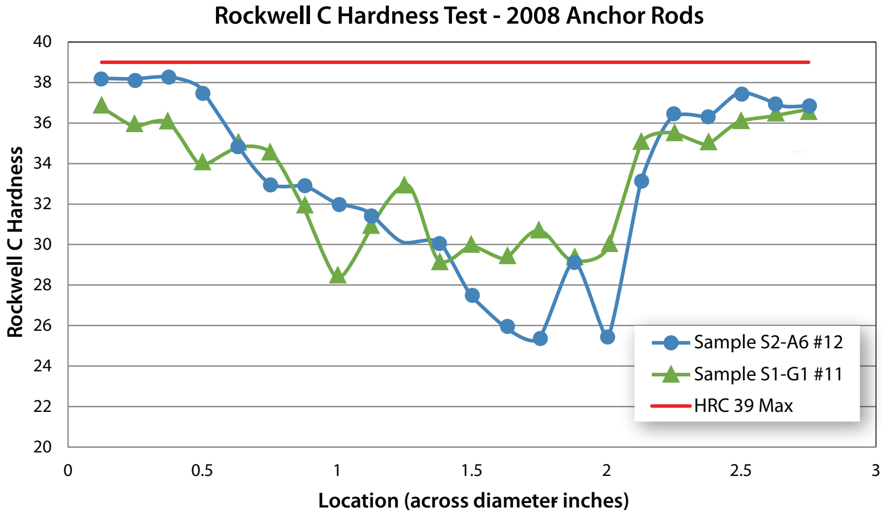
505 Sample Tensile Test Results								
	2010 Samples				2008 Samples			
Identification	B3-A2	S4-D7	S3-E7	B4-A7	S2-A6 #12	S2-A6 #2	S1-G1 #11	Requirement
Yield Strength (ksi)	143	138	139	143.1	149	146	136	115 min.
Tensile Strength (ksi)	160	157	157	160.2	170	168	159	140 min.
Elongation in 2" Gage %	17.0	19.0	17.5	16.8	15.5	14.0	15.0	14 min.
Reduction of Area (%)	53.5	53.4	54.0	42.7	46.0	48.0	48.4	40 min.

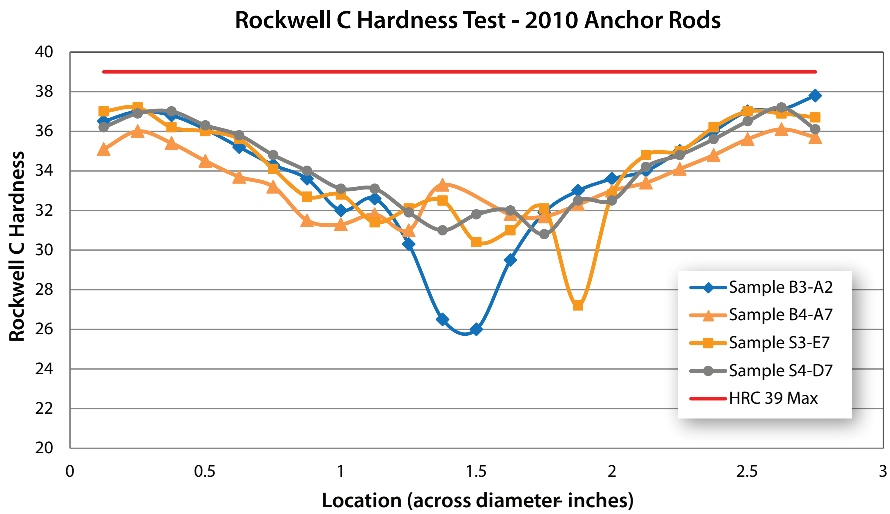
2. Charpy V-Notch Impact

Charpy V-Notch Impact Energy Test Results (ft-lb)											
	2010 Samples								2008 Samples		
Identification	B3-A2		S4-D7		S3-E7		B4-A7		S2-A6 #12	S2-A6 #2	S1-G1 #11
Temperature	40°F	70°F	40°F	70°F	40°F	70°F	40°F	70°F	70°F	70°F	70°F
Sample 1	35.5	37	37	37	38	38	39.5	39	18	15	13.5
Sample 2	38	38	37	38	37	37	36	39	18	14	13
Sample 3	37.0	38.0	37.5	37.0	37.0	37.0	37.5	37.0	17.0	15.0	14.0
Average	36.8	37.7	37.2	37.3	37.3	37.3	37.7	38.3	17.7	14.7	13.5

Figure 23 Mechanical Test Comparison 2008 vs. 2010 (Pier E2)

Hardness Testing





Is There Still a Risk of Hydrogen Embrittlement on the Remaining A354 Grade BD Rods?

As noted earlier, hydrogen embrittlement is a phenomenon that is time-dependent — it typically occurs over days or weeks after high tensile stress is applied. Therefore, because the remaining SAS rods have not failed over the 91 to 1,429 days since being tensioned (as of July 1, 2013), these rods have low risk of hydrogen embrittlement. In contrast, approximately 30 percent of the 2008 A354 grade BD rods (Item #1) failed between 3 and 10 days after tensioning, and more might have failed if the tension level had been maintained.

Additional supplemental tests, similar to those done on the Pier E2 2008 and 2010 rods, have been performed on a large sample of the remaining rods to verify their hardness and toughness along with their chemical and mechanical properties, to provide additional confirmation that hydrogen embrittlement risk is low. (Refer to Tests I, II, and III results below.)

What Is Stress Corrosion Cracking?

Stress Corrosion Cracking (SCC) is the growth of cracks in a corrosive environment, which can lead to unexpected sudden failure of normally ductile metals subjected to a tensile stress. Stress corrosion cracking is a phenomenon that exists when corrosion occurs in highly stressed high-strength steel, i.e., strength above 150 ksi. In the post-tensioning industry, highly stressed high-strength steel is usually placed inside of ducts, and capped and grouted after stressing to ensure the steel will not be subjected to a corrosive environment. If highly stressed steel is not protected, accelerated stress corrosion may occur, which could lead to stress corrosion cracking.

Stress corrosion cracking also occurs when hydrogen is generated from moisture, which then penetrates the steel that is susceptible to cracking and leads to embrittlement of the steel. Stress corrosion cracking can be considered a form of external hydrogen embrittlement and a longer-term phenomenon, as it is dependent upon corrosion taking place and, therefore, could take a long time to reach failure. In the situation where the steel is protected with galvanizing, a flaw or nick in the galvanizing will be a zone where the stress corrosion would be further accelerated.

SCC is a phenomenon that has existed since engineers have used ferrous materials; however, it has become a subject of greater importance with the introduction of higher-strength steels in higher-performance (highly stressed) applications and often in more aggressive corrosive environments, such as maritime applications including ships and offshore structures, where history has witnessed some catastrophic failures. Designers routinely consider the risks of stress corrosion and stress corrosion cracking in steel fabrications for boilers, pressure vessels, processing plants, high-pressure pipelines and marine structures. It is not a phenomenon restricted only to high-strength bolts, rods and tendons. In bridge construction, transient loads from traffic, wind or earthquakes do not result in stress corrosion cracking.

Is There a Risk of Stress Corrosion Cracking?

Stress corrosion cracking has been shown to be a concern for high-strength steel having a tensile strength above 150 ksi. Similar to hydrogen embrittlement, stress corrosion cracking is also time-dependent — except that, unlike hydrogen embrittlement, it tends to occur over years or decades of sustained tension, and is based on the commencement and rate of corrosion. So the longer-term concern is whether the remaining A354 grade BD rods are susceptible to stress corrosion cracking and, if so, when cracking may occur.

Therefore, it has been necessary to establish which rods are at risk for stress corrosion cracking and to perform additional analytical testing — using as a guide the published research of John.W. Fisher[12] and H.E. Townsend[13]. Fisher published a book entitled, *Guide to Design Criteria for Bolted and Riveted Joints, 2nd Edition,* Kulak, G.L., Fisher, J.W., Struik, J.H.A. in 1987. His re-

[12] John W. Fisher is a retired Professor Emeritus of Civil Engineering at Lehigh University in Bethlehem, Pennsylvania. During his 45-year career, Fisher has won nearly every medal and distinction in his field, and has examined most of the major failures of steel structures in America throughout the last four decades. One of his most recent endeavors was serving on a panel of national experts that investigated the collapse of the World Trade Center following the September 11, 2001 terrorist attack.

[13] H.E. Townsend is a Research Supervisor of the Corrosion Prevention Group within Homer Research Laboratories at Bethlehem Steel Corp., Bethlehem, Pennsylvania.

search found that electroplated and hot-dipped zinc coatings decrease the resistance to stress corrosion cracking in direct levels of stress intensities. Stress intensity is a function of the diameter of the rod and the tension the rod is placed under. In general, the larger the rod diameter and the higher the stress, the rod will have higher stress intensity. The other key factor in stress corrosion cracking is the hardness of the steel, especially at the surface of the material.

What Tests Are Being Conducted to Determine the Risk of Stress Corrosion Cracking and Why?

Protocols for determining stress corrosion cracking susceptibility have been established using five different tests, as described below.

Test I Test I is a test to conduct an *in-situ* hardness test on all accessible A354 grade BD rods and bolts on the SAS Bridge, thereby categorizing the susceptibility of each individual rod relative to hardness and applied stress intensity. The galvanized layer will be ground off the top surface of the rods using a grinder and sand paper. Once the surface is free from oil, grease, dust, rust, and surface coatings, measurements will be taken throughout the rod's diameter using a hardness tester that measures the depth of penetration of an indenter under a large load. A photo of such field testing on Pier E2 is shown below in Figure 24.

Figure 24 Photograph of Inspector Performing *In-situ* Hardness Test on Bearing Rod

Test II Test II is to conduct laboratory tests on a selected number of specimens or spares in order to determine a rod's hardness (Rockwell hardness test), toughness (Charpy V-Notch test) and chemical composition (Figure 25). In some locations there are rods installed in the bridge that have an excess or protruding length which, if cut off, could serve as a test specimen in a controlled laboratory environment. There are also some spare rods from the original manufactured lots that are available for laboratory testing.

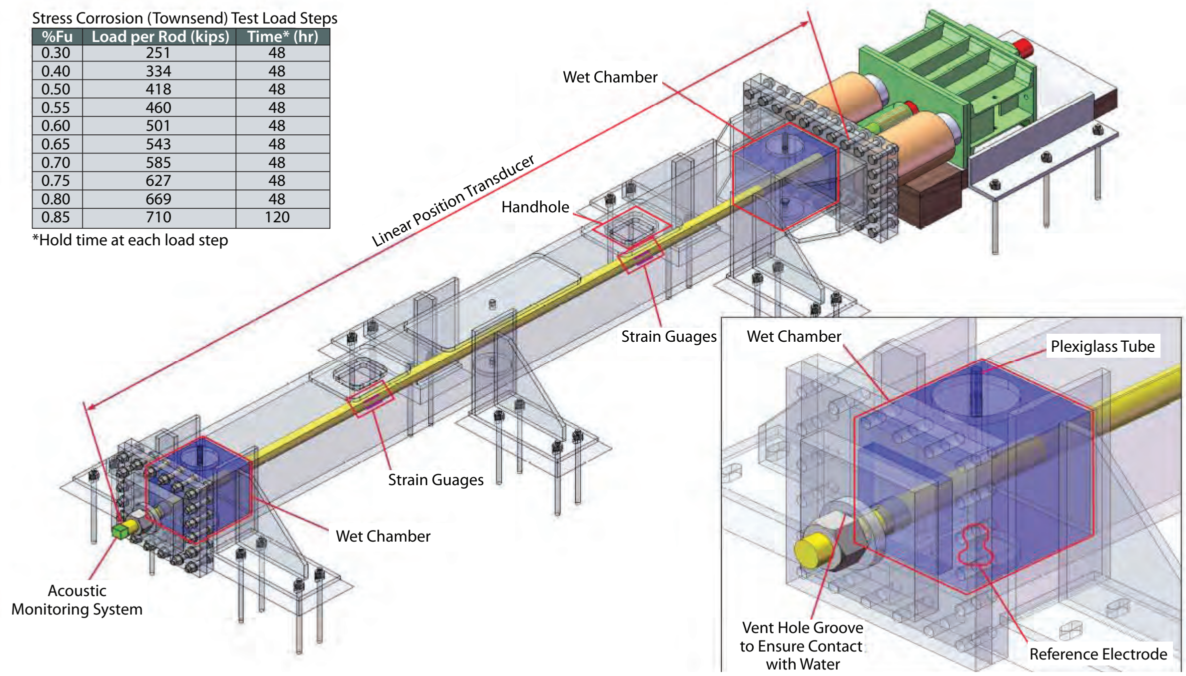
Figure 25 Charpy Toughness Test in Process (left)**; Tested and Untested Specimens** (right)

Test III Test III is to conduct laboratory testing (full size tension test, coupon tension test, Rockwell C hardness, Charpy, chemistry, fracture analysis) of full-sized rods extracted from the Pier E2 shear key and bearings (Items #2, 3, and 4 in Table 1) and the Tower Anchorage (Item #12 in Table 1). All the other full-sized tests can be performed on spare rods and bolts from the original manufactured lots. Under Test III, rods will be loaded to failure, and the failed rods will be examined and tested to determine their hardness, toughness, mechanical properties, and chemical composition. Figure 26 shows such a full-sized laboratory test underway.

Figure 26 Photograph of Full-Sized Rod Being Placed into Test Rig

Test IV Test IV (Townsend Test) is to conduct an accelerated stress corrosion test which replicates the earlier Townsend research (Figure 27). The results of Test IV will provide the curve against which the results from Tests I, II and III will be plotted and assessed in an updated and completed in the figure in the following section. The sample selection focuses on the rods subjected to the higher stress intensities (i.e., 0.7 Fu) with one additional sample from each diameter size of 2, 3 and 4 inches. Also of interest is whether there is a difference in susceptibility between rolled threads or cut threads and between galvanized and non-galvanized rods. Determining these differences will also require testing of rods with a diameter of 3½ inches under lower stress intensities.

Figure 27 3D Rendering of Stress Corrosion Test Platform for Test IV



Stress Corrosion (Townsend) Test Load Steps

%Fu	Load per Rod (kips)	Time* (hr)
0.30	251	48
0.40	334	48
0.50	418	48
0.55	460	48
0.60	501	48
0.65	543	48
0.70	585	48
0.75	627	48
0.80	669	48
0.85	710	120

*Hold time at each load step

Test V Test V (Raymond Test) involves laboratory tests of reduced size specimens from selected rods. These tests are of an accelerated type and measure the resistance of the material to stress corrosion cracking. The results of these tests are intended to supplement the data developed by the tests of full-sized rods in Test IV. These tests will include material from the 2008 rods to provide a basis of comparison. The test protocol is in the course of development.

A comprehensive plan has been prepared which takes sample rods from the bridge, utilizes spare rods as appropriate and tests additional rods exhibiting various diameters and finishes that have been placed on order with Dyson. When the test plan has been executed, all rod variations seen on the bridge will have been tested and assessed to determine the susceptibility of each individual rod to SCC. Rolled threads and cut threads are of interest since they exhibit different characteristics; rolled threads can offer a smoother thread profile due to the burnishing effect of the rolling operation, but this cold forming process can also increase the hardness at the thread end of the rods.

All tests, except for Tests IV and V, were completed by June 21, 2013. Tests II and III were conducted by independent laboratories in Texas and in Richmond, California. In consultation with Dr. Townsend, T.Y. Lin International prepared the shop drawings and the American Bridge/Fluor Joint Venture is constructing the equipment for Test IV, which is illustrated in Figure 27. The plans and protocols for Tests I through IV are shown in Figures 28 through 32.

Figure 28 Overall A354 Grade BD Rod Test Plan

SAS A354BD Bolt Tests

ID	Priority	Structural Component	Number of Bolts	Nominal Bolt Diameter [in]	Sustained Bolt Tension % Fu (UTS)	Number of Heats	Testing Plan - Sampling (minimum) I *in-situ* test	II Laboratory test (Note 1)	III Full Size Tension + Lab	IV Stress Corrosion test	V Incremental Step Load (ISL) Technique
1	TBD	Shear Key Anchor Bolts- Bottom (S1/S2)	96	3	0.70	7	90 +/-	10	1 (Note 9)	1 (Note 9)	10
2	A	Shear Key Anchor Bolts- Bottom (S3/S4)	96	3	0.70	1*	90	-	2**	2	2 (from test III)
	A	Pier E2 Bearing Bolts- Bottom Housing (B1, B2, B3, B4)	96	3	0.70	1*	74	-	2**	2	2 (from test III)
3	A	Shear Key Anchor Bolts-Top (S1/S2)	160	3	0.70	1*	160	6 (spares)	2 (spares)	-	2 (spares)
	A	Shear Key Anchor Bolts-Top (S3/S4)	160	3	0.70	1*	160	6 (spares)	2 (spares)	-	2 (spares)
4	A	Pier E2 Bearing Bolts- Top Housing (B1,B2,B3,B4)	224	2	0.70	1	224	7 (spares)	2 (spares)	1 (spare)	2 (spares)
5	-	Spherical Bearing Bushing Assembly Bolts	96	1	0.61	1	-	-	-	-	
6	-	Bearing Retainer Ring Plate Assembly Bolts	336	1	0.40	2	-	-	-	-	
7	B	PWS Strand Anchor Rods (Main Cable)	274	3-1/2	0.32	17	270 (Note 2)	43	1 (spare)	4***	4
8	C	Tower Saddle Tie Rods	25	4	0.68	1	19 (Note 3)	2 (spare)	1 (spare)	1 (spare)	1 (spare)
9	D	Tower Saddle Turned Rods (@ Splices)	100	3	0.45	2	20	2	-	-	
	D	Tower Saddle Turned Rods (@ Splices)	8	3	0.10	1					
10	-	Tower Saddle Grillage Bolts	90	3	0.10	1	-	-	-	-	
11	D	Tower Outrigger	4	3	0.10	1	-	-	1 (spare)	-	
12	C	Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)	388	3	0.48	2	194	6 (Note 5)	1 (Note 7)	1 (Note 7)	2 (Note 5)
13	C	Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts)	36	4	0.37	1	36	3 (Note 5)	-	-	1 (Note 5)
14	D	East Saddle Anchor Rods	32	2	0.10	1	16	2 (Notes 4 &7)	1 (spare)	-	
15	D	East Saddle Tie Rods	18	3	0.20	1	9	1	-	-	
16	D	Cable Bracket Anchor Rods	24	3	0.16	1	12	(Note 6)	-	-	
17	E	Bikepath Anchor Bolts at Pier W2	43	1-1/4	0.10	1	9	1	-	-	
18		E2 2013 Replacement Rods (CCO 312)	30	3	0.70		-	4	-	10 (Note 8)	4 (Note 8)

Notes: Notes:

1. Test at least one sample from each heat for Test II
2. Cut-off drill and tap hole @ end for testing. Sample lengths to be provided in separate attachment.
3. Test top surface of hex @ end of rod.
4. No Charpy tests due to limited available rod stick-out.
5. Samples for lab test shall be taken after tests I, III and IV are completed.
6. Same heat as PWS, no sampling necessary.
7. Sample already removed.
8. Rods to be tested shall be as follows
   + Galvanized: 3 Test IV
   + Black: 3 Test IV
   + Double Heat Treated, Galvanized: 2 Test IV
   + Double Heat Treated, Black: 2 Test IV
   + 1 rod Cut - half galv hafl black: Test V
   + 1 rod Double Heat Treated, half galv. Half black. Test V
9. If sample of sufficient length is available

*** 2 rolled thread samples &
2 cut thread samples

Page 6 of 7

Figure 29 Test I Protocol

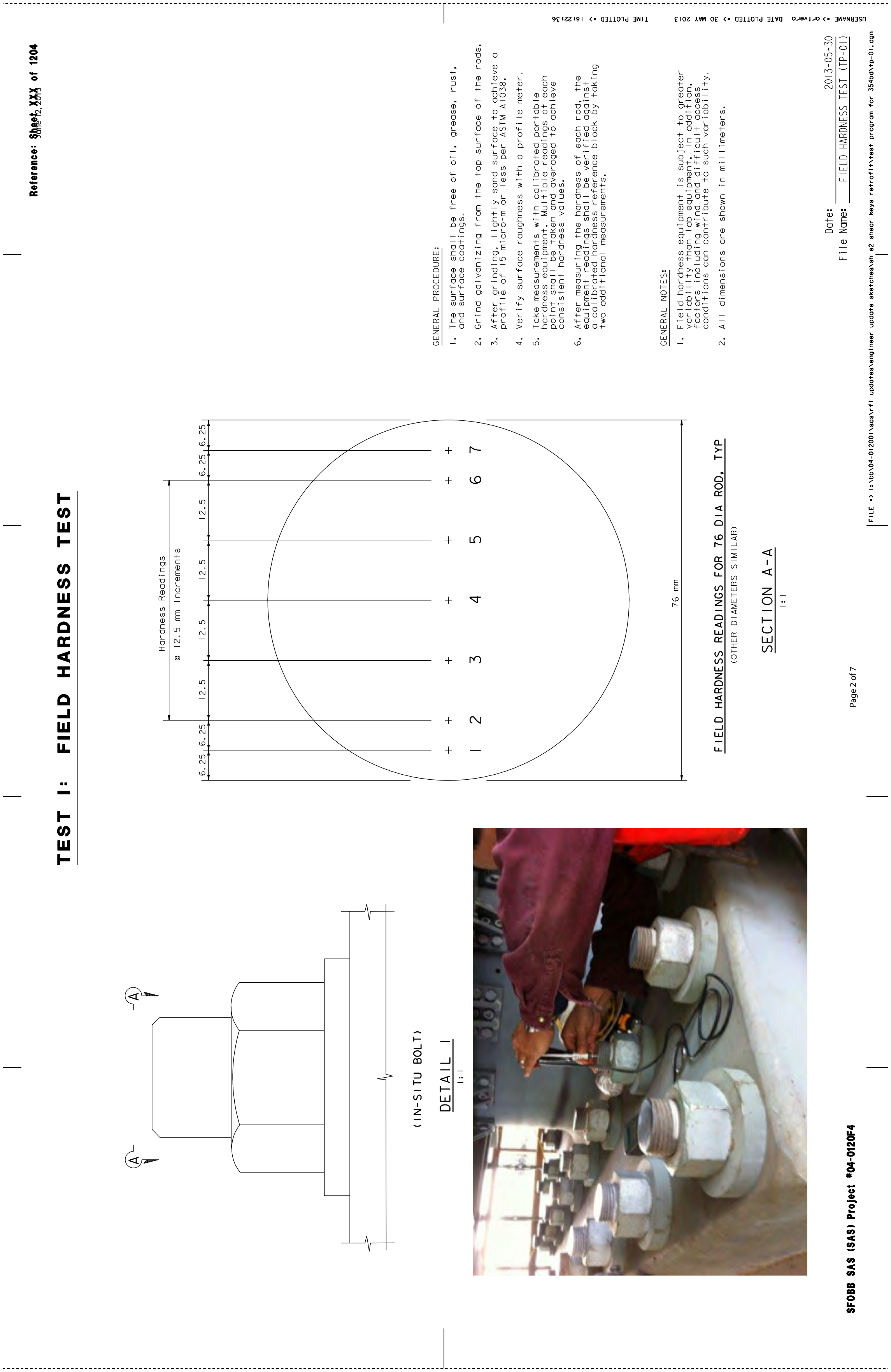


Figure 30 Test II Protocol

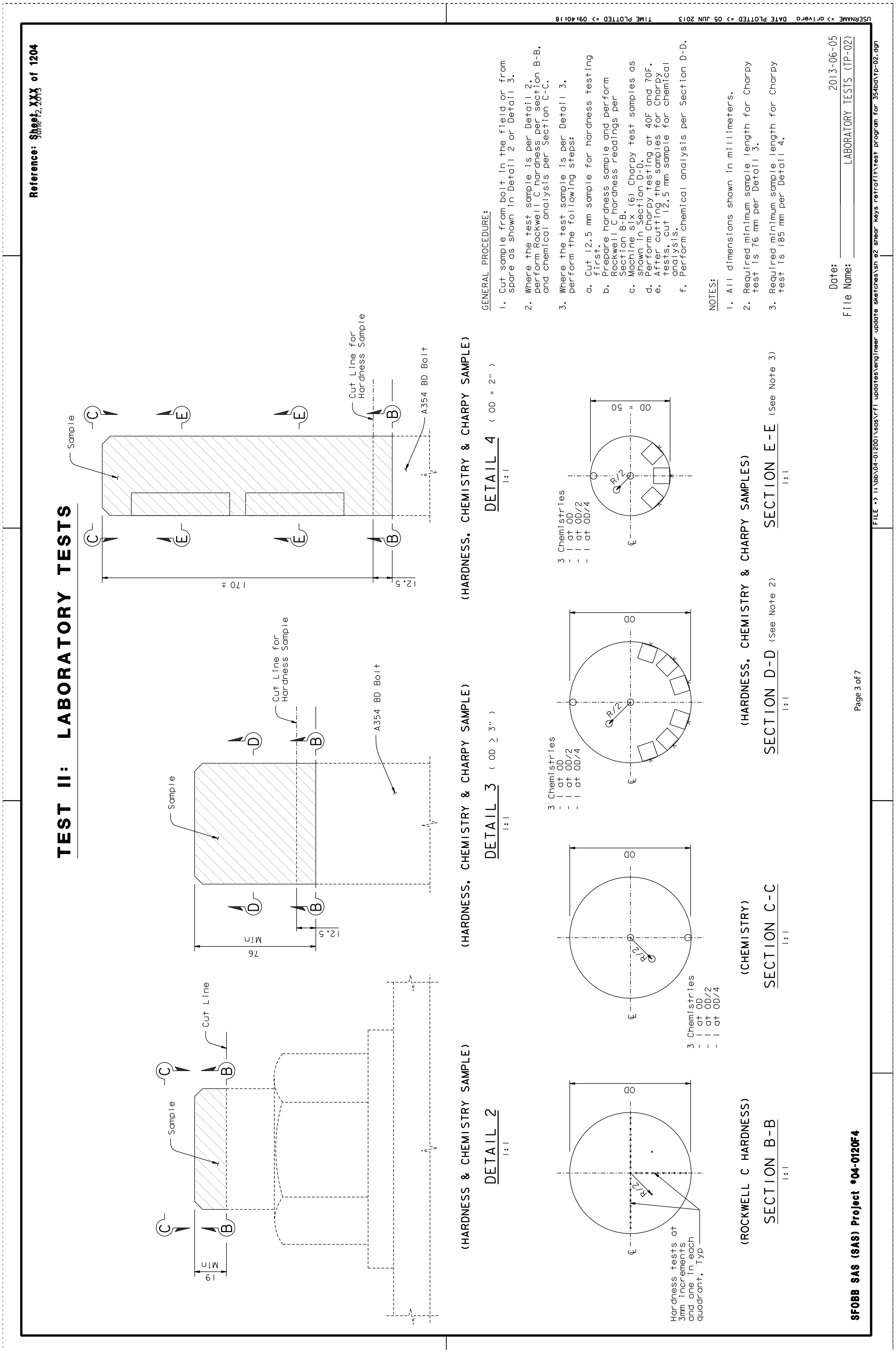


Figure 31 Test III Protocol

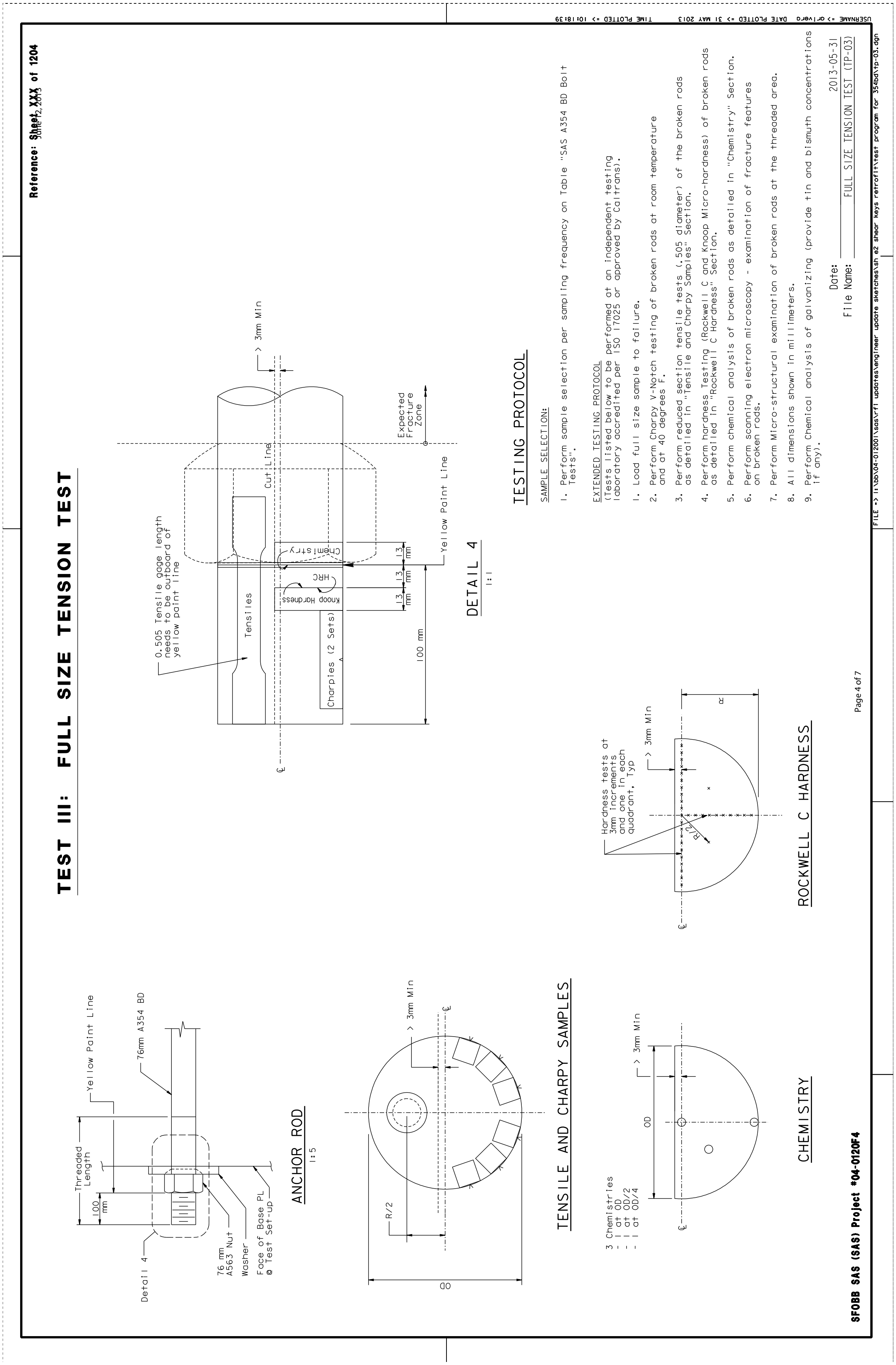
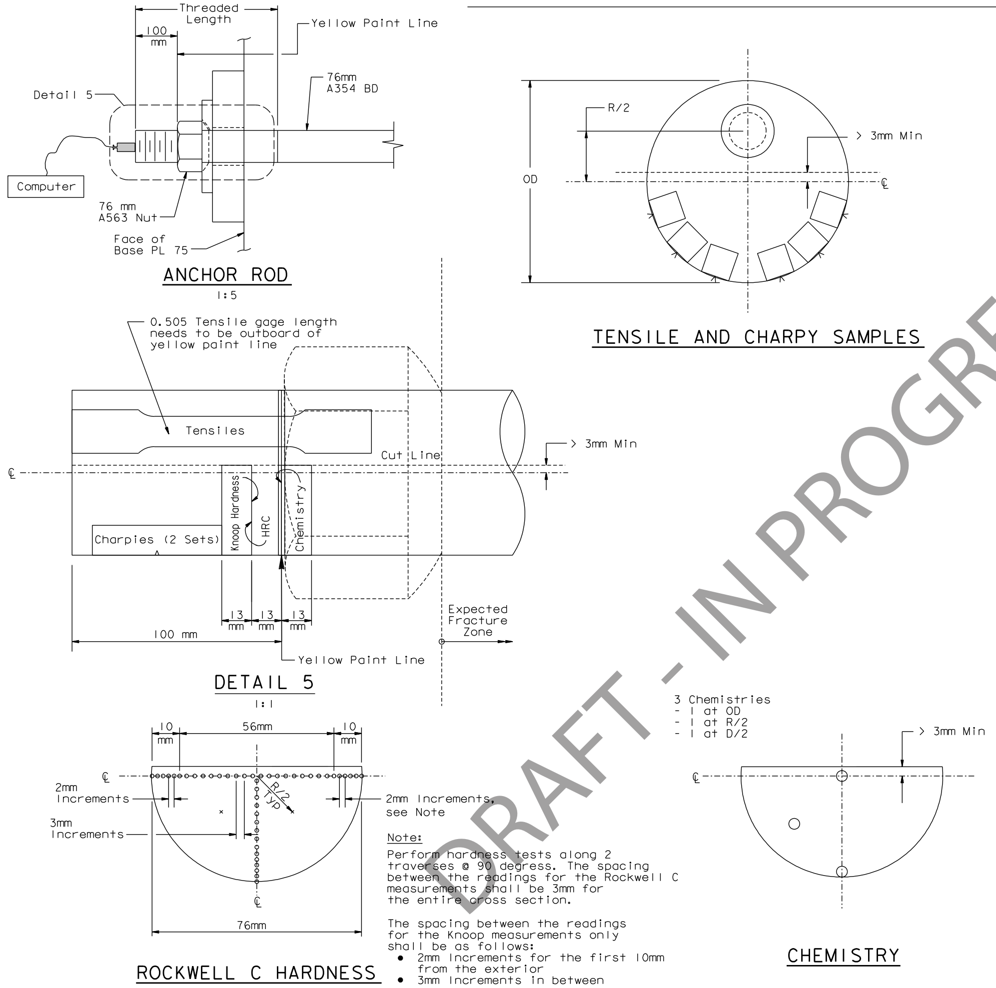


Figure 32 Test IV Protocol

Reference: Sheet XXX of 1204
June 12, 2013

TEST IV: STRESS CORROSION (TOWNSEND) TEST



TEST PROTOCOL:

This testing protocol was developed with the assistance of Dr. Herb Townsend, PhD,PE, Dr. Karl Frank, PhD,PE; and Mr. Doug Williams, PE.

SAMPLE SELECTION: 4 rods will be tested.

1. Prior to extraction, ABFJV shall reload the selected rods up to 0.75Fu and maintain the load for 24 hours.
2. After 24 hours, the rods shall be extracted and nondestructively tested.
3. Rods shall be cleaned to remove all contaminants and lubricants from the threads.
4. The samples shall be transported to the selected testing facility where the slow loading tests in a 3.5% NaCl solution will be performed as follows:

%Fu	Load per Rod (Kips)	Time* (hr)
0.30	251	48
0.40	334	48
0.50	418	48
0.55	460	48
0.60	501	48
0.65	543	48
0.70	585	48
0.75	627	48
0.80	669	48
0.85	710	120

* Hold time at each load step

5. The testing facility shall record the strain using 3 strain gauges, spaced 120 degrees apart around the circumference of the rod. The following data shall be recorded against time from the start of test: load hydraulic pressure), displacement, confirmation that water level is above rod, water ph, reference electrode reading, strain gauge readings, relevant acoustic emission events. Data shall be recorded at the beginning and end of each load step and at intervals not exceeding 8 hours.
6. After maintaining the load at 0.85 Fu for 5 days (120 hours) as shown above, load the samples to failure.
7. Transport the fractured sections to the fracture analysis lab for further assessment.
8. Perform Charpy V-Notch testing of broken rods at room temperature and at 70 degrees, per "Tensile and Charpy Samples" Section.*
9. Perform reduced section tensile tests (.505 diameter) of the broken rods as close to the fracture surface as possible. Tensile tests to be performed as detailed in "Tensile and Charpy Samples" Section.
10. Perform Rockwell C hardness and Knoop (Micro-hardness) testing per "Rockwell C Hardness" Section, and no closer than 1 rod diameter from the ends of each rod.
11. Perform chemical analysis of broken rods at the threaded area and at the shank. Chemical tests to be performed as detailed in "Chemistry" Section.
12. Perform scanning electron microscopy - examination of fracture features on broken rods.
13. Perform Micro-structural examination of broken rods at the threaded area.
14. Perform Chemical analysis of galvanizing (provide tin and bismuth concentrations if any).

Date: 2013-05-31
File Name: STRESS CORROSION (TOWNSEND) TEST (TP-04)

SFOBB SAS (SAS) Project #04-0120F4

Page 5 of 7

FILE => i:\bb\04-012001\sas\rfi updates\engineer update sketches\sh e2 shear keys retrofit\test program for 354bd\tp-04.dgn

USERNAME => orlvera DATE PLOTTED => 31 MAY 2013 TIME PLOTTED => 10:22:14

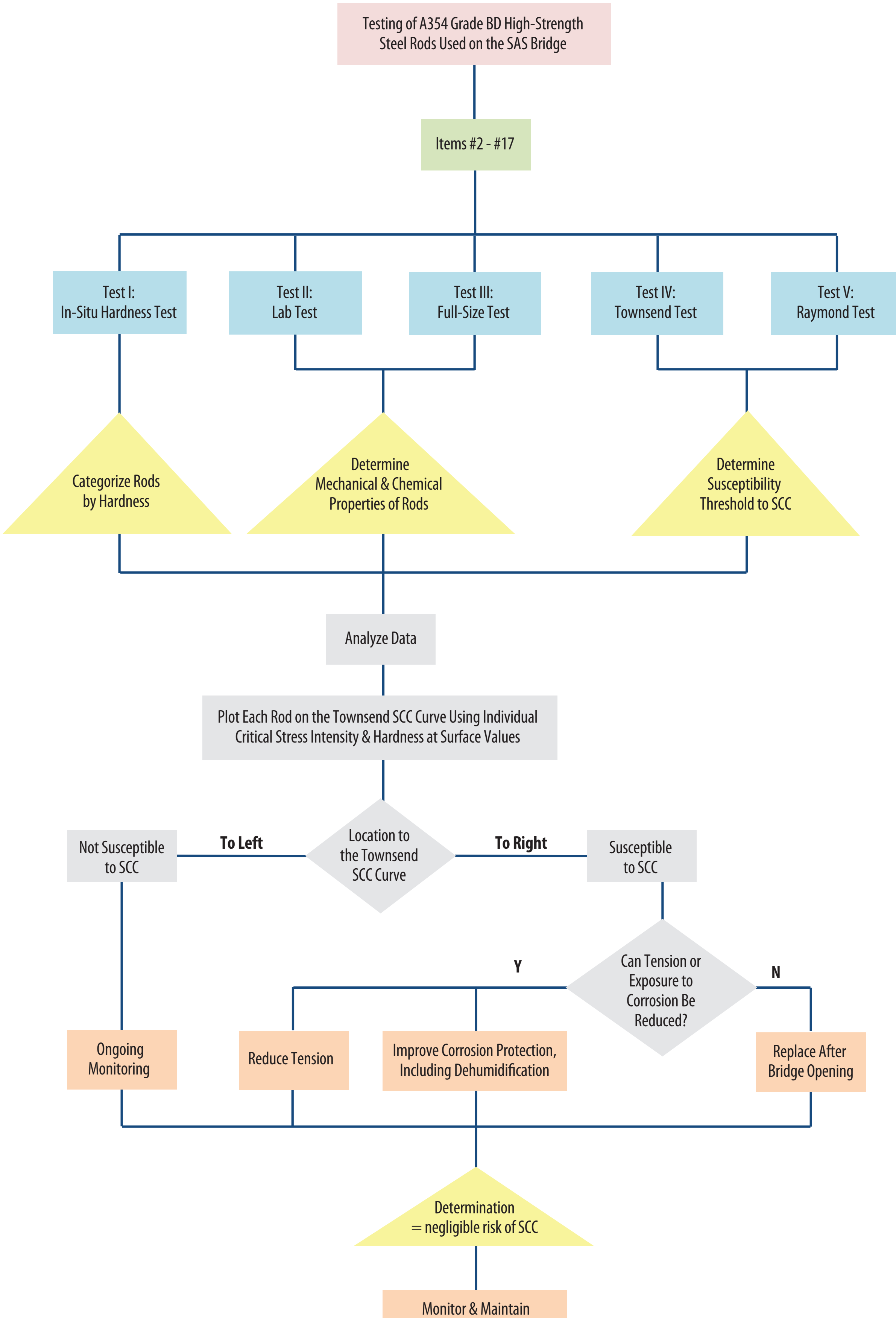
The flowchart displayed in Figure 33 shows the sequence of Tests I through V and at what point it can be determined that a group of rods has "passed the test" of longer-term stress corrosion cracking or, as deemed necessary, must be addressed by the implementation of mitigation measures. The tests are shown in the blue rectangular boxes; mitigating actions in the orange rectangular boxes; and the outcome/determination in the yellow triangle.

Tests I (*in-situ* hardness test), II (lab test) and III (full-sized test) were completed on June 21, 2013. The results from Tests I, II and III verified the mechanical properties of the rods and categorized each rod by hardness. The results from these tests are displayed in Table 13.

For Test IV (Townsend test), the construction of the test rig is underway and scheduled for completion in early July 2013 and used for the first group of Test IV samples. Additional test rigs are being constructed for Test IV to accommodate the range of ASTM A354 grade BD rod lengths and diameters. Results from Test IV will create the graphical curve per Townsend's research based on the ASTM A354 grade BD rods in the SAS Bridge and superimposed onto Figure 34. Rods that are to the left of the Townsend curve would be deemed not susceptible to stress corrosion cracking, while rods that are to the right of the curve will be deemed susceptible to stress corrosion cracking.

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

Figure 33 Determination for Susceptibility to Stress Corrosion Cracking



As noted earlier, critical to the development of stress corrosion cracking is the tension the rod is placed under, its diameter, threads and the hardness of the material. Individual rods with higher tension levels and hardness levels at, or above, 35 HRC should be further evaluated for risk for stress corrosion cracking, per guidance from Dr. Fisher. Test I results for *in-situ* surface hardness continue to show varying hardness levels across all tested rods. These results are plotted in Figure 34.

Upon completion of Test IV later this summer, a stress corrosion cracking susceptibility curve for the A354 Grade BD rods can be plotted on the critical stress intensity graph shown in Figure 34, displaying Critical Stress Intensity versus Surface Hardness. As described earlier, when the stress corrosion cracking susceptibility curve is included in Figure 34, in general, those rods plotted to the right of the curve will exhibit greater susceptibility to stress corrosion cracking over time. Conversely, rods plotted to the left of the curve are unlikely to be susceptible to stress corrosion cracking.

What Do the Results of Tests I, II and III Say About the Material Properties of the Other A354 Grade BD Rods?

Tests I, II and III for the other rods verified QC/QA test results and confirmed that the rods have low risk for near-term hydrogen embrittlement failures because the rods exhibit better metallurgical uniformity and improved toughness as compared to the failed 2008 rods. As noted earlier, these rods have performed successfully under tension from a minimum of three months to a maximum of nearly four years.

In regards to longer-term stress corrosion cracking, there are a number of rods that exhibit surface hardness that is in excess of 35 HRC, a point at which there is increased risk for stress corrosion cracking under sustained high tension. However, based on the tests, these rods also exhibit better metallurgical uniformity and improved toughness. Further, many of the remaining rods are not subject to high sustained tension levels or are located in dehumidified or sealed areas that provided additional corrosion protection. Further, stress corrosion testing is underway as part of Tests IV and V that will provide important data for further analysis and remediation of the rods. A summary of findings based on the material properties obtained from Tests I through III (unless otherwise noted) is contained in Table 13.

Figure 34 Critical Stress Intensity as Compared to Surface Hardness With *In-situ* Surface Hardness Test Data

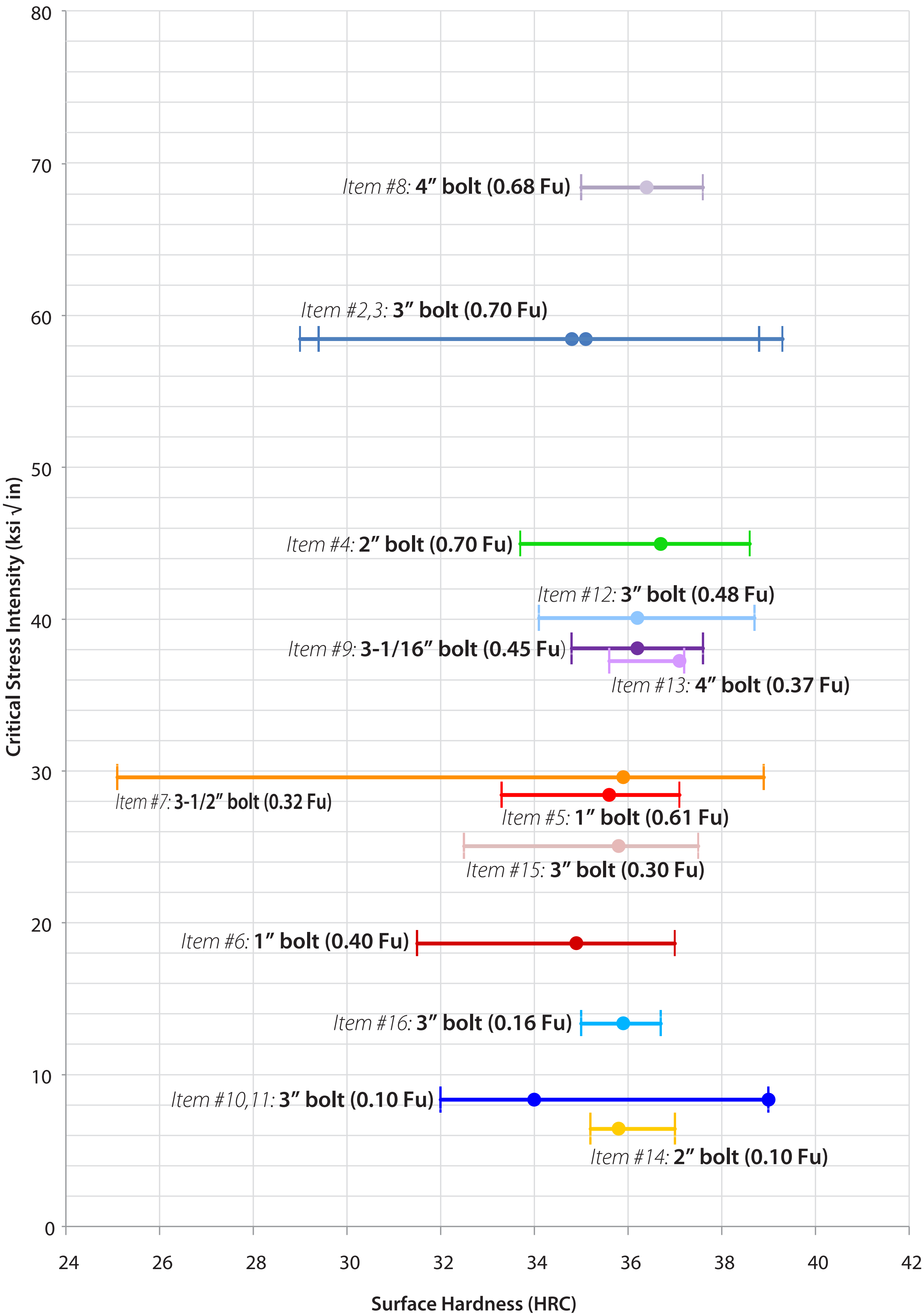


Table 13 Summary Results of Testing for Susceptibility to SCC

Item #		Microstructure	Surface Hardness of Tested Rods (HRC)	Ultimate Tensile Strength (ksi)
#1	Shear Key Anchor Rods (2008)	Incomplete martensitic transformation with alternate layers of ferrite and pearlite, and inclusions.	37.6 (avg) 36.9 – 38.2 (min – max) (Metallurgical Report)	165 (avg) 159 - 170 (min - max) (Metallurgical Report)
#2	Bearing & Shear Key Anchor Rods	Essentially Martensitic Structure	34.8 (avg) 29 – 39.3 (min – max)	158.6 (avg) 157 – 160.2 (min - max)
#3	Shear Key Rods (top)	Essentially Martensitic Structure	35.1 (avg) 29.4 – 38.8 (min – max)	157.3 (avg) 156.3 – 158.3 (min - max)
#4	Bearing Rods (top)	Essentially Martensitic Structure	36.7 (avg) 33.7 – 38.6 (min – max)	159.2 (avg) 158.4 – 159.9 (min - max)
#5	Bearing Assembly	Not tested	36 (avg) 33 – 37 (min – max) (QC/QA Data)	166 (avg) 161 - 174 (min - max) (QC/QA Data)
#6	Bearing Retainer Ring Plate Assembly	Not tested	35 (avg) 32 – 37 (min – max) (QC/QA Data)	166 (avg) 157 - 176 (min - max) (QC/QA Data)
#7	Parallel Wire Strands (PWS) Anchor Rods	Essentially Martensitic Structure	35.9 (avg) 25.1 – 38.9 (min – max)	158.5 (avg) 158.3 – 158.6 (min - max)
#8	Saddle Tie Rods	Essentially Martensitic Structure	36.4 (avg) 35 – 37.6 (min – max)	156.4 (avg) 151.3 – 161.5 (min - max)
#9	Saddle Turned Rods	Not tested	36.2 (avg) 34.8 – 37.6 (min – max)	148 (avg) 145 - 151 (min - max) (QC/QA Data)

For more information, see Appendix E.17 SAS A354BD Testing Program Results Tests I, II, and III; June 25, 2013

Mode of Fracture	Toughness CVN at 40° F (ft-lb)	Sustained Applied Tension	Secondary corrosion protection	Any rods failed after being tensioned
Brittle	13.5 (avg) 13 - 14 (min - max)	0.7	N/A	Yes
Ductile	37.3 (avg) 35.5 – 39.5 (min - max)	0.7	N/A	No
Ductile	36.9 (avg) 35 – 39 (min - max)	0.7	N/A	No
Ductile	26.7 (avg) 22 – 31 (min - max)	0.7	N/A	No
Ductile (QC/QA Data)	Not tested	0.6	Installed in a sealed and lubricated assembly.	No
Ductile (QC/QA Data)	Not tested	0.4	Installed in a sealed and lubricated assembly.	No
Ductile	39 (avg) 28 – 52 (min - max)	0.3	Dehumidified	No
Ductile	16.8 (avg) 13 – 18.5 (min - max)	0.7	Dehumidified	No
Ductile (QC/QA Data)	32.7 (avg) 11.5 – 54 (min - max)	0.5	Dehumidified	No

table continued on next page

Table 13 Summary Results of Testing for Susceptibility to SCC (continued)

Item #		Microstructure	Surface Hardness of Tested Rods (HRC)	Ultimate Tensile Strength (ksi)
#10	Saddle Grillage	Not tested	34 (avg) 32 – 34 (min – max) (QC/QA Data)	150 (avg) 147 - 153 (min - max) (QC/QA Data)
#11	Outrigger Boom	Essentially Martensitic Structure	39 (avg) 39 – 39 (min – max) (QC/QA Data)	167 (single test)
#12	Tower Anchor Rods (Type 1)	Essentially Martensitic Structure	36.2 (avg) 34.1 – 38.7 (min – max)	160.3 (avg) 154.9 – 163.3 (min - max)
#13	Tower Anchor Rods (Type 2)	Not tested	37.1 (avg) 35.6 – 37.2 (min – max	154 (single test)
#14	East Saddle Anchor Rods	Essentially Martensitic Structure	35.8 (avg) 35.2 – 37 (min – max)	150.4 (avg) 150.4 – 150.4 (min - max)
#15	East Saddle Tie Rods	Not tested	35.8 (avg) 32.5 – 37.5 (min – max)	148 (avg) 146 - 152 (min - max) (QC/QA Data)
#16	Cable Band Anchor Rods	Not tested	35.9 (avg) 35 – 36.7 (min – max)	156 (avg) 154 - 158 (min - max) (QC/QA Data)
#17	Bikepath Anchor Rods	Not tested	36 (avg) 35 – 37 (min – max) (QC/QA Data)	167 (avg) 160 - 179 (min - max) (QC/QA Data)

Mode of Fracture	Toughness CVN at 40° F (ft-lb)	Sustained Applied Tension	Secondary corrosion protection	Any rods failed after being tensioned
Ductile (QC/QA Data)	Not tested	0.1	N/A	No
Ductile	Insufficient sample length to perform test	0.1	N/A	No
Ductile	40.5 (avg) 32 – 56 (min - max)	0.5	Dehumidified	No
Ductile (QC/QA Data)	31.7 (avg) 23 – 46 (min - max)	0.4	Dehumidified	No
Ductile	27 (avg) 24 – 32 (min - max)	0.1	N/A	No
Ductile (QC/QA Data)	17.8 (avg) 17 – 18.5 (min - max)	0.2	N/A	No
Ductile (QC/QA Data)	Not tested	0.2	N/A	No
Ductile (QC/QA Data)	Not tested	TBD	N/A	No

7. Toll Bridge Program Oversight Committee (TBPOC) Findings

This Toll Bridge Program Oversight Committee (TBPOC) investigation entailed an exhaustive review of contract documents — including all the relevant and available QC, QA as supplied by Caltrans and other project records — and detailed discussions with key project staff to validate our technical reasoning. TBPOC also sought advice and informed opinions from both national and international experts to understand all the issues and to determine the industry's current best practice approach. We present our findings below:

1. As noted in the joint Caltrans - American Bridge/Fluor Joint Venture metallurgical report dated May 7, 2013, "The [2008] 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." However, that same report concluded that "the steel rods comply with the basic mechanical and chemical requirements of ASTM A354 grade BD," which was the basis of the rod specification selected by the designer and owner of the project.

2. The three factors contributing to the risk of failure due to hydrogen embrittlement are the presence of hydrogen, high tensile loads and the susceptibility of the material to hydrogen. The contract specifications for the East Span did not consider the unique requirements of the seven different rod locations on the SAS Bridge. One specification was inappropriately applied to all locations. In addition, it was inappropriate to adapt the fastener specification modified during the Richmond-San Rafael Bridge Retrofit Project, where the A354 grade BD galvanized rods were deployed underwater at low tension (snug tight), to the E2/T1 Marine Foundation and SAS Superstructure contracts for the new east span, where similar rods were deployed above water and at considerably higher tension levels.

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

4. There was inadequate consideration given to the combined effect of high-strength rod material requirements and corrosion protection. The fastener selection process was completed during design, and the corrosion protection specification was modified during advertisement and construction. There was no subsequent return discussion to the fastener selection decision.

5. There was inadequate consideration of alternative corrosion protection treatments, given well-known concerns about the risk of hydrogen embrittlement from hot-dipped galvanizing of A354 grade BD rods. In particular, alternative treatments such as Geomet®, or greased and sheathed, or painted solutions should have been more fully considered depending on the various sizes and applications. A life cycle cost analysis should have been prepared for the various rod alternatives and the various methods of long-life corrosion protection.

6. The fastener specification for the E2/T1 Marine Foundations and SAS Superstructure contracts relied too heavily on generic ASTM standards and should have included special provisions reflecting a better understanding of the principles of the ASTM standards to guard against hydrogen embrittlement. In particular, the contracts should have more clearly addressed the following four requirements: 1) maximum steel hardness and through consistency, 2) minimum steel toughness, 3) magnetic particle testing, and 4) a time-dependent test of the rods under tension prior to their installation on the new bridge. As one peer review panelist noted: "National Standards are the minimum. You still need to do good engineering."

7. The construction of Pier E2 should not have allowed for water to collect during the construction process. The collection of water in their support cylinders may have exacerbated the embrittlement of the 2008 high-strength steel rods. Because the rods were to be embedded in concrete, it was infeasible to remove and replace them. In the words of one engineer, "A good design should not be so sensitive to bad material."

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

9. It took a considerable amount of time, including significant manual effort, to assemble the QC/QA information for the SAS rods. In the case of the E2/T1 Marine Foundation contract, much of the information has not been located for a contract completed as recently as 2008. Such information is vital not only for an investigation of materials failure such as this, but for routine maintenance and major rehabilitation of the SAS over its 150-year design life.

Responsible Parties

The design and construction of the Self-Anchored Suspension (SAS) Bridge of the new East Span involved several responsible parties:

- Caltrans is the owner and operator of the New East Span;
- T.Y. Lin International/Moffatt & Nichol Design Joint Venture is the Engineer of Record;
- American Bridge/Fluor Joint Venture is the contractor for the SAS Superstructure; and
- Kiewit/FCI/Manson Joint Venture is the contractor for the SAS E2/T1 Marine Foundation.

These parties are responsible for the actions that led to the following findings:

- T.Y. Lin International/Moffatt & Nichol Design Joint Venture, American Bridge/Fluor Joint Venture and Caltrans jointly share responsibility for Findings 1 and 7.
- T.Y. Lin International/Moffatt & Nichol Design Joint Venture and Caltrans jointly share responsibility for Findings 2, 3, 4, 5 and 6.
- American Bridge/Fluor Joint Venture and Caltrans jointly share responsibility for Finding 8.
- Caltrans is responsible for Finding 9.

8. Toll Bridge Program Oversight Committee (TBPOC) Decisions and Actions

On July 18, 2005, Governor Schwarzenegger signed Assembly Bill 144 (AB 144) into law and thereby authorized a $1 increase in the seismic surcharge to be implemented no earlier than January 1, 2007. AB 144 also created the Toll Bridge Program Oversight Committee (TBPOC) to provide oversight and project control for the Toll Bridge Seismic Retrofit Program and the Benicia-Martinez Bridge Project in California.

The TBPOC is composed of the Director of the Department of Transportation (Caltrans), the Executive Director of the Bay Area Toll Authority (BATA), and the Executive Director of the California Transportation Commission (CTC). The TBPOC's project oversight and control activities include, but are not limited to, reviewing bid specifications and documents, providing field staff to review ongoing costs, reviewing and approving significant change orders and claims in excess of $1 million (as defined by the Committee) and preparing project reports.

In April 2013, the TBPOC initiated an investigation into the failed A354 grade BD rods. As part of the investigative process, the TBPOC did the following:

- Conducted four workshops on April 17, May 1, May 15, and June 25, 2013;
- Met over 25 times in person or by phone;
- Consulted with industry experts, the Seismic Peer Review Panel, and the Federal Highway Administration Review Panel;
- Reviewed over 50 documents and over 5,000 pages of material;
- Briefed the Bay Area Toll Authority (BATA) and the BATA Oversight Committee on March 27, April 10, April 24, May 8, and May 29, 2013;
- Presented and responded to questions during the California Senate Transportation and Housing Committee hearing on May 14, 2013; and
- Briefed members of the Bay Area State Legislative Delegation on June 6, 2013.

On May 8, 2013, the TBPOC received a presentation from T.Y. Lin International/Moffatt & Nichol Design Joint Venture on the retrofit strategy options to address the failed 2008 rods. The TBPOC selected the steel saddle option because it would meet all the design requirements and objectives of the project. The Seismic Peer Review Panel agreed with this selection.

On the same day, the TBPOC sent a letter to the California Division Administrator of FHWA requesting its assistance to conduct an independent review of the findings and recommendations concerning the high-strength steel rods on the new East Span.

Based on the findings above and review of the 17 different types of A354 grade BD rods used on the East Span, there are four categories into which this report classifies the 2,306 high-strength steel rods on the SAS Bridge:

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

How Will Rods at Risk of Stress Corrosion Cracking Be Addressed?

Stress corrosion cracking is time-dependent — it occurs over years or decades of sustained tension and is based on the commencement and rate of corrosion. The longer-term concern is whether the remaining A354 grade BD rods are susceptible to stress corrosion cracking and, if so, when cracking may occur. Like hydrogen embrittlement, there are three factors that contribute to stress corrosion cracking — susceptible material, high tensile stress and hydrogen-related corrosion. Without any one of these three conditions, stress corrosion cracking will not occur. Assuming susceptible material, the mitigation strategy for avoiding stress corrosion cracking is to either reduce the tensile stress or reduce the potential for corrosion. The option of reducing the tension can only be considered by the designer after evaluating any excess redundancies in the completed structure versus the original design requirements. Mitigation of corrosion can be achieved in a number of ways, by the application of galvanizing, painting, greasing and sheathing, or dehumidifying to remove moisture (a source of hydrogen). If reducing applied tension or mitigating corrosion cannot be achieved in another fashion, then replacement of rods may be necessary.

As noted earlier, galvanizing is designed to protect the underlying steel from corrosion. However, galvanizing also can be detrimental to highly stressed, high-strength steels because a small penetration through the coating will establish a galvanic reaction that accelerates the generation of hydrogen at the point of the penetration, thereby introducing a strong source of environmental hydrogen.

Rod-by-Rod Resolution

Based on the data available from Tests I through III and the design criteria and expected structural performance of the SAS, Table 14 depicts a provisional approach for remediating the stress corrosion cracking potential of the various A354 grade BD rods on the SAS Bridge. These recommendations are provisional pending completion of the final tests (referred to as the Townsend Test and Raymond Test). In no case, however, do we expect the remaining tests to indicate that any rods, other than the failed Item #1 anchor rods, will need to be replaced before opening the new East Span to traffic. The risk of near-term hydrogen embrittlement has passed. The potential for longer-term stress corrosion cracking can be managed safely and effectively after the SAS is placed into service.

The rod-by-rod resolution displayed in Table 14 is explained in the following section, which details the remediation strategy for each grouping of A354 grade BD rods. The "Replacement Before Opening" is self-explanatory. "Replace After Opening" and "Augment Dehumidification" are anticipated to occur before the end of 2014 to take advantage of the efficiencies offered by the existing contractor and the temporary work platforms that are still in place. Rods confirmed by T.Y. Lin International/Moffatt & Nichol Design Joint Venture, the Engineer of Record, as being appropriate for reduction in tension will be adjusted as soon as the load distribution ceases to change due to construction activities. The rods labeled "Accept and Monitor" do not require remediation and illustrate the fact that the original specification used for all 17 rod locations was only appropriate for fasteners installed under low tension. All high-strength rods will require routine and periodic maintenance.

Table 14 Recommended Rod-by-Rod Resolution

	Construction	Maintenance			
Location	Replace Before Opening	Replace After Opening	Reduce Tension	Augment Dehumidification	Accept and Monitor
E2	1. Shear Key Anchor Rods* (bottom) *replaced by steel saddle retrofit	2. Bearing & Shear Key Anchor Rods (bottom) 3. Shear Key Rods (top) 4. Bearing Rods (top)			5. Bearing Assembly (bushings) 6. Bearing Retainer Ring Plate Assembly
Anchorage				7. PWS Anchor Rods	
Top of Tower		11. Outrigger Boom	8. Saddle Tie Rods 9. Saddle Turned Rods		10. Saddle Grillage
Bottom of Tower			12. Tower Anchor Rods (Type 1) 13. Tower Anchor Rods (Type 2)		
East Saddle					14. East Saddle Anchor Rods 15. East Saddle Tie Rods
East Cable					16. Cable Band Anchor Rod
W2					17. Bikepath Anchor Rods

Note: Dehumidification is already in place for the Top of Tower, Bottom of Tower and Main Cable Anchorage.

Pier E2

Items #1 - 3″ diameter Pier E2 S1 and S2 Anchor Rods:

The clamping capacity of these failed rods will be replaced by the retrofit, and the retrofit must be completed prior to bridge opening.

Items #2 - 3″ diameter Pier E2 B1-B4, S3 and S4 through Anchor Rods:

These rods have a design stress of 0.7 Fu. At the tested range of surface hardness, these rods will be highly susceptible to stress corrosion cracking. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods or full replacement to substantially eliminate the likelihood of stress corrosion cracking.

Item #3 - 3″ diameter Pier E2 S1 through S4 Upper Housing Rods:

These rods have a design stress of 0.7 Fu. At the tested range of surface hardness, these rods will be highly susceptible to stress corrosion cracking. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods or full replacement to substantially eliminate the likelihood of stress corrosion cracking.

Item #4 - 2″ diameter Pier E2 Bearing Upper Housing Rods:

These rods have a design stress of 0.7 Fu. At the tested range of surface hardness, these rods will be highly susceptible to stress corrosion cracking. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods or full replacement to substantially eliminate the likelihood of stress corrosion cracking.

Item #5 - 1″ diameter Pier E2 Bearing Assembly Rods:

These rods have a design stress of 0.61 Fu. These rods satisfactorily passed ASTM A143 embrittlement tests prior to installation. Although the rods themselves are inaccessible, the bearing assemblies that contain these rods will be monitored for performance. Further, these rods are sealed and lubricated inside the bearing, which should prove to be an effective deterrent to corrosion.

Item #6 - 1″ diameter Bearing Retainer Plate Assembly

These rods have a design stress of 0.4 Fu and satisfactorily passed ASTM A143 embrittlement tests prior to installation. Although the rods themselves are inaccessible, the bearing assemblies that contain these rods will be monitored for performance. Further, the rods are sealed and lubricated inside the bearing, which should prove to be an effective deterrent to corrosion.

Anchorage

Item #7 - 3.5″ diameter Parallel Wire Strand (PWS) Anchor Rods:

These rods have a design stress of 0.32 Fu. The *in-situ* surface hardness of these rods varies widely from 25 to 39 HRC, with many rods at the upper end of that range, which indicates high susceptibility to stress corrosion cracking. PWS Anchor Rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, which will tend to mitigate stress corrosion cracking for the PWS rods. Since it is not possible to reduce the tension levels on these rods and replacement is not desirable, the near-term remediation strategy is to ensure adequate dehumidification to reduce the corrosion potential in the cable anchorage chamber. This may require augmenting the planned level of dehumidification in the chamber.

Top of Tower

Item #8 - 4″ diameter Tower Saddle Tie Rods:

These rods had an installation design tension of 0.41 Fu, which increased to 0.68 Fu upon completion of load transfer. The *in-situ* surface hardness of these rods (from 35 to 38 HRC) indicates high susceptibility to stress corrosion cracking. However, the rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, which will tend to mitigate stress corrosion cracking for these rods. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods or augmenting dehumidification to substantially eliminate the likelihood of stress corrosion cracking.

Item #9 - 3″ diameter Tower Saddle Turned Rods:

These rods have a design stress of 0.45 Fu, which was only necessary during the erection of the tower saddle segments at the top of the Tower. After erection of the cable and load transfer, these rods are no longer required due to the radial forces imposed by the main cable through the tower saddle. Further, these rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, which will tend to mitigate stress corrosion cracking. Although the surface hardness of these rods indicates high susceptibility to stress corrosion cracking, the combined possibility for lowering of tension and augmenting dehumidification should provide an effective means to substantially reduce the risk of stress corrosion cracking.

Item #10 - 3″ diameter Saddle Grillage:

These rods have a design stress of 0.1 Fu. The low tension of these rods indicates low susceptibility to stress corrosion cracking, but these rods have high surface hardness. Ongoing monitoring is recommended.

Item #11 - 3″ diameter Outrigger Boom:

These rods have a design stress of 0.1 Fu. The low tension of these rods indicates low susceptibility to stress corrosion cracking, even though these rods have high surface hardness. As the tower boom has not yet been installed, these rods should be replaced prior to boom installation.

Bottom of Tower

Item #12 - 3″ diameter Tower Anchor Rods:

These tower anchor rods were installed under the E2/T1 contract. These rods have a design stress of 0.48 Fu. The *in-situ* surface hardness of the material is between 34 and 39 HRC. These rods are located on the exterior and interior face of the tower base. Replacing the interior rods will be difficult, if not impossible, due to the overall length of these rods and the limited amount of headroom available inside of the tower. However, these rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, which will mitigate stress corrosion cracking. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods.

Item #13 - 4″ diameter Tower Anchor Rods:

These tower anchor rods were installed under the E2/T1 Marine Foundation Contract. These rods have a design stress of 0.37 Fu. The *in-situ* surface hardness of the material is between 35 and 37 HRC. These rods are housed inside a water-tight, dehumidified chamber so moisture is not readily present, which will mitigate stress corrosion cracking. Pending full evaluation of all test results, the designer may consider lowering the stress in these rods. Ongoing monitoring is recommended.

East Saddles

Item #14 - 2″ diameter East Saddle Anchor Rods:

These rods have a design stress of 0.1 Fu. The low tension of these rods indicates low susceptibility to stress corrosion cracking. Ongoing monitoring is recommended.

Item #15 - 3″ diameter East Saddle Tie Rods:

These rods have a design stress of 0.2 Fu. The low tension of these rods indicates low susceptibility to stress corrosion cracking. Ongoing monitoring is recommended.

East Cable

Item #16 - 3″ diameter Cable Band Anchor Rods:

These rods have a design stress of 0.16 Fu. The low tension of these rods indicates low susceptibility to stress corrosion cracking. Ongoing monitoring is recommended.

Top of Pier W2

Item #17 - 1.2" diameter Bikepath Anchor Rods:

The final design of the bikepath has not yet been completed since this is dependent upon the demolition of the existing East Span. These rods may be modified or replaced at a later time if necessary, but ongoing monitoring is recommended at a minimum.

Revised Specifications for Replacement Rods

Additional high-strength steel rods are to be purchased to replace the 2010 rods on Pier E2 that have been selected for testing. The remediation strategy outlined in the previous section also will require procurement of additional high-strength steel rods. Caltrans has applied supplementary specifications for the rods identified for replacement, which limit the ultimate tensile strength, minimum toughness, maximum hardness and impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring homogeneous metallurgical structure. Caltrans also will be performing the time-dependent hydrogen embrittlement "pull test" required by ASTM F606 and the Townsend and Raymond Tests to determine the replacement rods' susceptibility to stress corrosion cracking. Finally, alternative corrosion protection methods will be evaluated. The Toll Bridge Program Oversight Committee will review and approve all major actions regarding procurement of replacement rods.

Maintenance Plan

One of the tasks of the design team is to prepare Bridge Maintenance and Inspection Manuals for each of the major components of the East Span shown in Figure 1, as each component is completed. Each set of manuals will provide documentation on the design, documentation on the construction, load ratings, detailed inspection procedures for each major element, an initial "baseline" inspection and inventory, sources and reference material, and post-seismic inspection and repair procedures. The manuals are to be used primarily by personnel engaged by Caltrans to perform routine inspections, in-depth or special inspections, and routine maintenance on the East Span structures. Regarding the A354 grade BD rods, the maintenance plan for these elements of the SAS Bridge will include existing baseline information (test data, etc.), required monitoring and testing, inspection and testing methods to be employed, required intervals, required routine and periodic maintenance, protocols for notification and action when required, and actions required after an extreme event (earthquake, vessel collision, etc.).

Bridge Opening

The TBPOC concludes that it is safe to open the new East Span after replacing the capacity lost by the failed 2008 rods. It is unnecessary to replace any of the remaining rods (Items #2 through #17) before the bridge opening since the risk of near-term hydrogen embrittlement has passed, and especially in light of the safety imperative of moving traffic off the seismically deficient existing East Span Bridge. While some rods are highly susceptible to longer-term stress corrosion cracking, ample evidence exists than none are at high risk of near-term fracture. Replacement of rods on the east pier should begin prior to the contractor demobilizing, in order to take advantage of the current scaffolding and support structure in place.

New Versus Old Bridge

As noted earlier, the San Francisco-Oakland Bay Bridge was designated by the California State Legislature as an important lifeline structure because of its location along transportation corridors crucial for emergency relief and economic revitalization following a major earthquake. Because of the Bay Bridge's designation as a lifeline structure, Caltrans required that the East Span Replacement Project incorporate design elements that exceed the requirements of standard seismic bridge design. The East Span Replacement Project was designed to withstand probable ground motions from largest earthquake to occur once every 1,500 years.

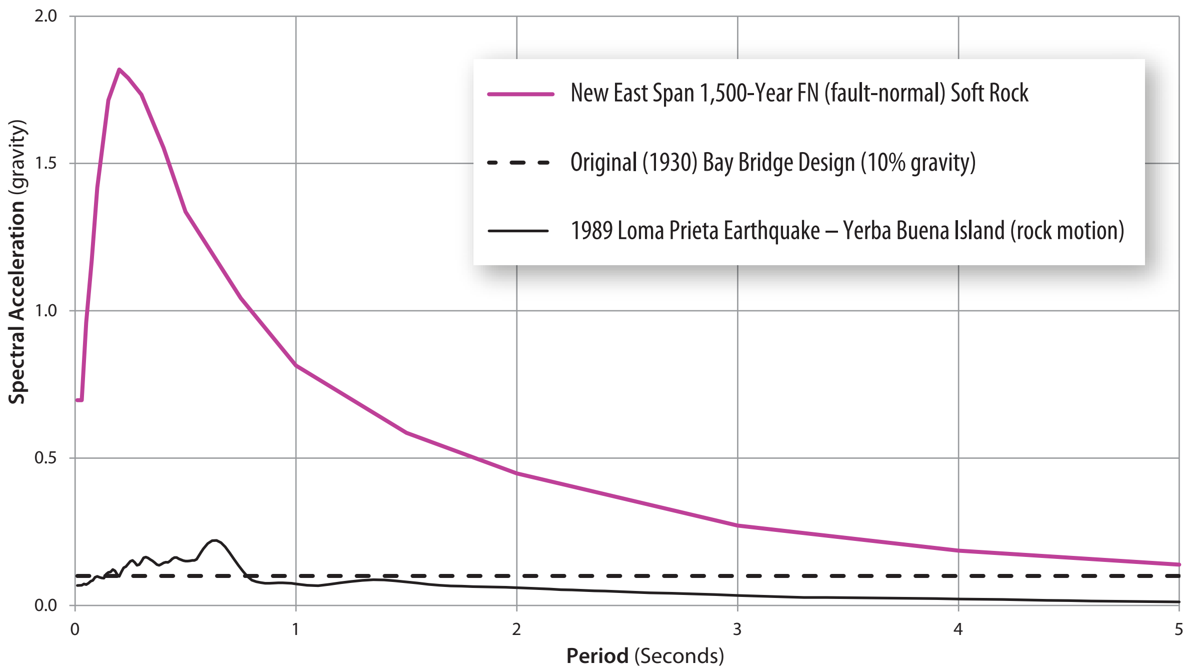
An excerpt from the Governor's Board of Inquiry[20] refers to the design of the old bridge that the new East Span will replace:

> "The [1935] Bay Bridge was designed for 10% of g (the acceleration due to Earth's gravity) earthquake accelerations, comparable to the levels specified in the 1930 Uniform Building Code for buildings. It should be noted that knowledge of damaging earthquake motions was very limited at this time; the first few measurements of strong ground motions were not measured until the 1933 Long Beach earthquake."

Ground accelerations have been plotted in Figure 35 comparing the design of the new East Span with the 1936 East Span and recorded Loma Prieta earthquake accelerations in 1989. The Loma Prieta earthquake was a 6.9-magnitude earthquake centered nearly 60 miles away from the Bay Bridge that still caused the partial collapse of a section of the existing cantilever structure. While the west spans of the Bay Bridge have been fully retrofitted, the east span of the bridge is still vulnerable until replaced.

[20] Governor's Board of Inquiry on 1989 Loma Prieta Earthquake, page 26.

Figure 35 Comparison of Ground Accelerations



9. Review by the Seismic Peer Review Panel

The TBPOC has briefed the Seismic Peer Review Panel regarding its investigative report on the A354 grade BD high-strength steel rods on the SAS Bridge. The Seismic Peer Review Panel has provided comments on the report, and will provide its written review to the TBPOC under separate cover.

Seismic Peer Review Panel

Dr. Frieder Seible, Chair, Dean Emeritus, University of California at San Diego

Dr. Seible is Chair of the Caltrans Seismic Advisory Board. He is also Dean and Professor Emeritus of the Jacobs School of Engineering, University of California at San Diego. He developed the Charles Lee Powell Structural Research Laboratories, which serve as a worldwide resource for full-scale testing and analysis of structures. He is a member of a federal Blue Ribbon Panel on Bridge and Tunnel Security. Seible received a Dpl. Ing. from the University of Stuttgart, a Masters of Science degree from the University of Calgary, and a Ph.D. from the University of California at Berkeley, all in civil engineering. Dr. Seible is a member of the National Academy of Engineering.

Dr. John Fisher, Emeritus Professor of Civil Engineering, Lehigh University

Dr. Fisher was Professor of Civil Engineering at Lehigh University from 1969 until 2002, when he became Professor Emeritus. He was Director of the Engineering Research Center on Advanced Technology for Large Structural Systems (ATLSS) since its establishment in May 1986 until September 1999. Dr. Fisher is a graduate of Washington University, St. Louis, Missouri, with M.S.CE and Ph.D. degrees from Lehigh University. A structural engineer, Dr. Fisher is a specialist in structural connections, the fatigue and fracture of riveted, bolted and welded structures, the behavior and design of composite steel-concrete members, and the performance of steel bridges. Dr. Fisher has published over 275 articles, reports and books in scientific and engineering journals. Dr. Fisher is a member of the National Academy of Engineering.

Dr. I.M. Idriss, Emeritus Professor of Civil Engineering, University of California at Davis

Dr. Idriss is a Professor in the Department of Civil Engineering and Environmental Engineering at the University of California at Davis. He completed his Ph.D. degree at the University of California at Berkeley. Dr. Idriss served as a member of Governor George Deukmejian's Board of Inquiry on the Loma Prieta Earthquake. Since 1998, Dr. Idriss has been a member of Caltrans' Seismic Peer Review Panel for the design and construction of the new East Span of the San Francisco-Oakland Bay Bridge. Dr. Idriss is a member of the National Academy of Engineering.

Toll Bridge Program Oversight Committee

Steve Heminger, Chair

Mr. Heminger is the Executive Director of the Metropolitan Transportation Commission (MTC), which is the regional transportation planning and finance agency for the nine-county San Francisco Bay Area. Since 1998, MTC has served as the Bay Area Toll Authority (BATA) responsible for administering all toll revenue from the seven state-owned bridges. Mr. Heminger is also Chair of the Toll Bridge Program Oversight Committee, overseeing construction of the new East Span Replacement Project. Mr. Heminger was appointed by House Democratic Leader Nancy Pelosi to serve on the National Surface Transportation Policy and Revenue Study Commission, which helped chart the future course for the federal transportation program. In addition, he is Chairman of the Board of Trustees for the Mineta Transportation Institute, a member of the Board of Directors for the Association of Metropolitan Planning Organizations, and a member of the Executive Committee for the Transportation Research Board. Mr. Heminger received his Master of Arts degree from the University of Chicago and a Bachelor of Arts degree from Georgetown University.

Malcolm Doughterty

Mr. Dougherty is the Director of the California Department of Transportation (Caltrans), which builds, maintains and operates 50,000 lane-miles of the California transportation system. He is also a member of the Toll Bridge Program Oversight Committee. Before being appointed Director of Caltrans, Mr. Dougherty served as Chief Deputy Director, where he advised and assisted the Director with all aspects of Caltrans' policies and operations. He also served as District Director in the Fresno area. As District Director, he was responsible for Planning, Project Management, and Maintenance for the district's five counties, as well as the Capital Project Delivery Program for the Central Region, which spans from the Pacific coastline to Nevada, and from Amador County to Kern County. Dougherty's career also includes management positions in Design, Project Management, Maintenance, and Traffic Operations. Mr. Dougherty is a graduate of Rutgers University with a Bachelor of Science in Civil Engineering.

Andre Boutros

Mr. Boutros is Executive Director of the California Transportation Commission (CTC), which is the agency responsible for programming and funding several billion dollars annually for transportation projects throughout California in partnership with regional transportation agencies and Caltrans. He is also a member of the Toll Bridge Program Oversight Committee. Mr. Boutros has more than 28 years of direct involvement in the development and preservation of California's transportation infrastructure. He has been a staff member to the CTC since 2007, and has served as the Chief Deputy Director since 2008, where he was responsible for the day-to-day operations of the CTC, acting as the chief of staff and the primary policy advisor to the Executive Director and the Commission. Prior to joining the CTC, Mr. Boutros held numerous technical, management and leadership positions with Caltrans.

10. Glossary of Terms

A354 Grade BD Anchor Rod An anchor rod conforming to the ASTM A354 specification, which covers the chemical and mechanical requirements of quenched and tempered alloy steel bolts, studs and other externally threaded rods 4 inches and under in diameter. Grade BD indicates level of strength, where the minimum tensile strengths are 140 ksi for 25/8-inch to 4-inch diameter rods and 150 ksi for ¼-inch to 2½-inch diameter rods.

American Iron and Steel Institute (AISI) An association of North American steel producers, developed in response to the need for a cooperative agency in the iron and steel industry for collecting and disseminating statistics and information, carrying on investigations, providing a forum for the discussion of problems and generally advancing the interests of the industry.

American Society for Testing and Materials (ASTM) Originally established in 1898 as the American Society for Testing and Materials, ASTM International is one of the largest organizations in the world to develop voluntary consensus standards for test methods and material specifications. One of its missions is to contribute to the reliability of materials, products, systems and services. The ASTM is made up of over 40 technical committees (e.g., Committee A-1 on Steel, Committee C-1 on Concrete). Its consensus approach to standards has resulted in the development of more than 12,000 ASTM standards today. For a description of the ASTM standards that are relevant to this project, refer to Table 6.

Anchor Rod A rod used to attach objects or structures to concrete. There are many types of anchor rod (also referred to as anchor bolts), consisting of designs that are mostly proprietary to the manufacturing companies. All consist of a threaded end, to which a nut and washer can be attached for the external load.

Bearing A device located between the bridge structure and a supporting pier or abutment.

Caltrans Bridge Design Specifications Manual All local bridges (in California) on and off the National Highway System shall be designed in accordance with the current edition of the *Caltrans Bridge Design Specifications Manual*. The 1995 version of the *Caltrans Bridge Design Specifications Manual* was in effect when the design of the new East Span Replacement Project began. The next update to the manual was released in April 2000.

Caltrans Standard Specifications Manual The *Caltrans Standard Specifications Manual* provides specifications that are standard to Caltrans construction projects.

Charpy V-Notch Test An impact test in which a rectangular specimen with a 'V' shaped notch cut into the midpoint of the length is struck by a pendulum mounted striker. The energy that is absorbed in fracture is calculated by comparing the height to which the striker would have risen had there been no specimen to the height to which it actually rises after fracture of the specimen.

Compression A force that pushes or presses toward the center of an object or from the ends toward the middle of a structural member.

Corrosion For steel, corrosion is an oxidation process where iron combines with oxygen to form iron oxide, which is commonly known as rust.

Deck The roadway portion of a bridge, including shoulders. Most bridge decks are constructed as reinforced concrete slabs.

Ductility The ability of a material to deform before it fractures.

Elongation Elongation is a measure of the ductility of a material (the percentage stretch in the length of a test specimen). It is the amount of strain (e.g., bending) a material can experience before failure in a tensile test. A ductile material will record a high elongation, while brittle materials, such as ceramics, tend to show very low elongation.

Fatigue A cyclic cracking mechanism that is progressive and localized, caused by repetitive loading over time and is more commonly transgranular.

Ferrite The metallurgical structure of iron alloys that forms if the material cools slowly from a high temperature

Flash Pickling A process of pickling where the steel product is dipped for less than 30 seconds to avoid a source of hydrogen that could be absorbed by the steel.

Galvanic Corrosion A phenomenon where the combination of different materials together with moisture establish an electric cell. Depending upon the material combination, one will become the anode and the other the cathode. The anode will display signs of corrosion while gas bubbles may be generated at the cathode.

Galvanic Protection An engineering solution to reduce or eliminate the corrosion of structural members where reliance on coatings may be impractical. Sacrificial anodes are attached to the structure so that a galvanic corrosion cell is established causing the anode to oxidize, thereby protecting the cathode (the structural member). The level of cathodic protection or rate of corrosion of the anode is dependent upon the ratio of the surface areas being exposed to the connecting moisture.

Galvanizing A means of applying a protective zinc coating that will corrode in preference to the steel substrate.

Girder A horizontal structural member supporting vertical loads by bending. Larger girders typically are made of multiple metal plates that are welded or riveted together.

Grade BD A level of strength specified in ASTM A354 that is higher than Grade BC and equal in strength to ASTM A490. The minimum tensile strengths of Grade BD rods are 140 ksi for 25/8-inch to 4-inch diameter rods and 150 ksi for ¼-inch to 2½-inch diameter rods. Unlike ASTM A490 however, the A354 grade BD specification is unrestricted in its configuration. Since A490 are heavy hexagon headed structural bolts and do not exceed 1½-inches in diameter, specification A354 Grade BD should be considered for anchor bolts, threaded rods, other styles of headed bolts, and bolts larger than 1½-inches in diameter where similar mechanical properties are desired. A354 Grade BD rods do not require a magnetic particle test, as is required by the A490 specification.

Greased and Sheathed System An alternative method for corrosion protection that does not require heat or chemical treatment that could potentially alter the chemical composition or mechanical properties of the steel. Steel rods are placed in a sheath (or sleeve/tube) and a corrosion-inhibiting wax or grease is injected into the sheath.

Hardness A measure of a material's ability to resist abrasion and indentation.

Hardness Rockwell C Scale (HRC) The Rockwell scale is a hardness scale based on indentation hardness of a material. There are several alternative scales, the most commonly used being the "B" and "C" scales. HRC is a gauge of the hardness of a material based on a test that measures the depth of penetration by an indenter under a large load compared to the penetration made by a preload. As specified in ASTM D785, the indenters for the Rockwell test include steel balls of several specific diameters and a diamond cone penetrator having an included angle of 120° with a spherical tip having a radius of 0.2 mm.

High-Strength Steel (HSS) Bolts A steel bolt or rod having a tensile strength greater than 125,000 pounds per square inch (125 ksi).

Hot-Dip Galvanizing (HDG) A process of dipping fabricated steel into a kettle or vat of molten zinc. While the steel is in the kettle, the iron metallurgically reacts with the molten zinc to form a tightly-bonded alloy coating that provides superior corrosion protection to the steel. It is the process of coating iron, steel or aluminum with a thin zinc layer, by passing the metal through a molten bath of zinc at a temperature of around 850° F (455° C). A typical hot-dip galvanizing process includes a cleaning operation that removes impurities, such as stains, inorganic contaminants, rust or scale, followed by a water rinse, application of flux and then submersion in the molten zinc.

Hydrochloric Acid Dip See "Pickling."

Hydrogen Embrittlement (HE) A phenomenon where atomic hydrogen migrates and accumulates in steel, causing weakness in the crystalline lattice and often observed by separation at the grain boundaries. This weakening of the steel is known as "hydrogen embrittlement."

Kilopounds per square inch (ksi) A unit of stress resulting from a force of one kilopound-force applied to an area of one square inch.

Magnetic Particle Testing (MT) A non-destructive method for detecting cracks and other discontinuities at or near the surface in ferromagnetic materials, such as iron, nickel, cobalt and some of their alloys. Magnetic particle testing may be applied to raw material, semi-finished material, finished material and welds, regardless of heat treatment or lack thereof.

Martensite The metallurgical structure of iron alloys that forms if the material cools quickly from a high temperature. Generally this material is hard and brittle until tempered.

Mechanical Galvanizing A room temperature process in which zinc coatings are applied to rods without electricity (which is used for electroplating) and without heat (which is used for hot-dip galvanizing). The process of mechanical galvanizing is similar to hot-dip galvanizing, in that a steel piece is cleaned and rinsed. The piece is then tumbled in a mixture of various-sized glass beads and a predetermined amount of water, with small amounts of chemicals and powdered zinc added periodically. Collisions between the glass beads, zinc and the piece cause a cold-welding process that applies the zinc coating. Powdered zinc is added until the specified thickness is attained. The room temperature process ensures no chance of re-tempering or softening high-strength pieces against hydrogen embrittlement, because the steel pieces are also never exposed to acid pickling in the process.

Mechanical Grit (or Abrasive) Blasting An operation of forcibly propelling a stream of abrasive material against a surface under high pressure to smooth a rough surface, roughen a smooth surface, shape a surface or remove surface contaminants.

Mid-radius A point at half the distance from the center of a circle to the perimeter (e.g., the radius divided by 2)

Morphology The characteristics of a fractured surface (e.g., interganular, transgranular, cleavage)

Non-Conformance Report (NCR) A report outlining a deviation from product, process, procedure or compliance specifications.

Non-Destructive Evaluation (NDE) Also referred to as non-destructive testing or non-destructive inspection, this evaluation does not damage the test object. Technologies for non-destructive evaluation include MT, x-ray and ultrasound, which may be used to detect such defects as cracking and corrosion.

Notice of Proposed Resolutions (NPR) A report prepared in response to a non-conformance report (NCR) that outlines disposition and corrective action to bring the condition back into conformance.

Orthotropic Box Girder (OBG) A structural steel box that is stiffened either longitudinally or transversely, or in both directions, to allow the roadway to directly bear vehicular loads and to contribute to the bridge structure's overall load-bearing behavior.

Pearlite The metallurgical structure that forms together with ferrite when iron alloys are cooled slowly from a high temperatures.

Pickling A metal surface treatment used to remove surface impurities such as stains, inorganic contaminants, rust or scale from ferrous metals, copper and aluminum alloys. A solution called pickle liquor, which contains strong acids, is used to remove the surface impurities. It is commonly used to descale or clean steel in various steelmaking processes. The primary acid used is hydrochloric acid, thus pickling also is described as a hydrochloric acid dip.

Pier A vertical structure that supports the ends of a multi-span superstructure at a location between abutments.

Pier E2 The first pier east of the main tower of the self-anchored suspension span, and where the twin steel orthotropic box girder roadways rest.

Post-Tensioning A method of stressing concrete using steel rods or cables that are stretched after the concrete has hardened. This stretching of the rods or cables puts the concrete in compression, with the compressive stresses designed to counteract the tensile (tension) forces on the concrete once it is under load.

Self-Anchored Suspension (SAS) The SAS portion of the new East Span of the Bay Bridge connects the Yerba Buena Island Transition Structures with the Skyway. A single continuous cable is anchored within the eastern end of the roadway, carried over the tower, wrapped around the two side-by-side decks at the western end carried back over the tower and re-anchored at the eastern end of the roadway. The 2,047-foot-long SAS has a single 525-foot-tall steel tower, and is designed to withstand a massive earthquake.

Shear A force that causes parts of a material to slide past one another in opposite directions to cause separation.

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

Skyway The Skyway portion of the new East Span of the Bay Bridge is a 1.2-mile-long, elevated viaduct between the SAS and the Oakland Touchdown, with two parallel roadways that will accommodate five lanes of traffic plus two 10-foot-wide shoulders in each direction.

Specifications A document that explains material and construction requirements of the bridge structure.

SSPC-SP 10 A standard established by the Society for Protective Coatings that covers the requirements for near-white blast cleaning of unpainted or painted steel surfaces by the use of abrasives. A near-white metal blast-cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter, except for staining as noted. Random staining shall be limited to no more than 5 percent of each unit area of surface as defined, and may consist of light shadows, slight streaks or minor discolorations caused by stains of rust, stains of mill scale or stains of previously applied coating.

Strain-age Embrittlement A phenomenon where steel becomes very brittle in areas of high stress when exposed to elevated temperatures. At room temperature, strain-aging happens very slowly, but at elevated temperatures, like those used in the galvanizing process, strain-aging can happen very quickly. When the steel has incurred enough stress due to strain-aging, it can become embrittled. The most common type of embrittlement encountered in the hot-dip galvanizing process is strain-age embrittlement.

Stress Corrosion Cracking (SCC) A phenomenon that can occur in any highly stressed high-strength steel component. In the context of this report, the SC phenomenon may occur on galvanized high-strength steel rods in cases where the zinc layer is incomplete and a relatively small area of high-strength, highly stressed steel is exposed. The ratio of surface areas between the anode (zinc) and the cathode (exposed steel) may be such that a strong galvanic reaction occurs, with the separation of oxygen and hydrogen molecules in water and the migration of oxygen to form zinc oxide and the release of atomic hydrogen free to be absorbed into the metallurgical structure of the exposed steel.

Susceptibility to Hydrogen Embrittlement High-strength steels over 150 ksi possess a metallurgical structure that has an affinity for hydrogen, which is increased through the application of heat or when subjected to high levels of stress.

Tensile Load A force that attempts to pull apart or stretch an object.

Tension A force that stretches or pulls on a material.

Tension Member Any member of a truss that is subjected to tensile (tension) forces.

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

Ultimate Tensile Strength The maximum stress that a material can withstand while being stretched or pulled before failing or breaking. Tensile strength is the opposite of compressive strength and the values can be quite different.

Vacuum Degassing A process where molten metal (commonly steel) is placed in a vacuum in order to remove excess hydrogen or carbon. During the production process, a product’s metal parts or components can become infused with excess amounts of these gases. As a result, unwanted imperfections and side effects can impact the integrity or performance of the metal. Vacuum degassing to remove carbon not only reduces imperfections, but brings a larger added benefit. By removing the carbon, the metals become more ductile, or easily shaped and formed through cold metalworking.

Yerba Buena Island Transition Structures The Yerba Buena Island Transition Structures connect the SAS to the Yerba Buena Island tunnel and provide the transition from the East Span’s side-by-side traffic to the upper and lower decks of the tunnel and the West Span. The new structures are made of cast-in-place reinforced concrete, with 13 supports (footings and columns).

Zinc Electroplating A process by which electricity is used to provide a protective zinc coating to metallic substances, such as nuts, bolts, fasteners, automotive parts and many other hardware items. Zinc electroplating is a common and cost-effective way to protect against the effects of corrosion. Using the electroplating process changes the chemical and physical properties of a metal.

11. List of Key Agencies and Organizations Involved

California Department of Transportation (Caltrans) Created in 1895, Caltrans is the owner and operator of more than 50,000 miles of California's highway and freeway lanes, including the Bay Area's seven state-owned toll bridges.

California Transportation Commission (CTC) Established in 1978 by Assembly Bill 402, the CTC replaced and assumed the responsibilities of four independent bodies the California Highway Commission, the State Transportation Board, the State Aeronautics Board and the California Toll Bridge Authority. The CTC is responsible for the programming and allocating of funds for the construction of highway, passenger rail and transit improvements throughout California.

Bay Area Toll Authority (BATA) Created by the California Legislature in 1997, BATA administers the base $1 auto toll on the San Francisco Bay Area's seven state-owned toll bridges. In January 1998, BATA began operations under the Metropolitan Transportation Commission. In August 2005, the California Legislature expanded BATA's responsibilities to include administration of all toll revenue and joint oversight of the toll bridge construction program with Caltrans and the CTC.

Toll Bridge Program Oversight Committee (TBPOC) Assembly Bill 144 established the TBPOC to be accountable for delivering the Seismic Retrofit Program. Members of the TBPOC are:

- **Steve Heminger,** Executive Director, BATA (Chair)
- **Andre Boutros,** Executive Director, CTC
- **Malcolm Dougherty,** Director, Caltrans

Project Management Team (PMT) The PMT is responsible for reporting to the TBPOC. Members of the PMT are:

- **Tony Anziano,** Toll Bridge Program Manager, Caltrans
- **Andrew B. Fremier,** Deputy Executive Director, BATA
- **Stephen Maller,** Deputy Executive Director, CTC

Caltrans Seismic Safety Peer Review Panel This Panel provides guidance and technical expertise related to complex structure projects with major seismic design exceptions and issues. Members of this Panel are:

- **John Fisher,** Emeritus Professor of Civil Engineering, Lehigh University
- **I.M. Idriss,** Emeritus Professor of Civil Engineering, University of California at Davis
- **Frieder Seible,** Vice Chair of the Caltrans Seismic Advisory Board and Dean Emeritus, University of California at San Diego

Federal Highway Administration (FHWA) Review Panel This Review Panel was responsible for conducting an independent review of the findings and recommendations contained in this report. Members of the Review Panel were:

- **Joey Hartmann,** Team Leader, Office of Bridge Technology, FHWA Headquarters
- **Greg Kolle,** Structures Engineer, FHWA California Division Office
- **Myint Lwin,** Director, Office of Bridge Technology, FHWA Headquarters
- **Justin Ocel,** Research Structural Engineer, FHWA Highway Research Center
- **Waider Wong,** Senior Structural Engineer, Resource Center, FHWA Headquarters

Metallurgical Investigative Team In May 2013, a metallurgical investigative team was tasked with examining the cause of the failure of the A354 grade BD high-strength steel rods manufactured in 2008. Members of this team were:

- **Rosme Aguilar,** Chief of Structural Materials Testing Branch, Caltrans
- **Salim Brahimi,** President, IBECA Technologies and Consultant to American Bridge/Fluor Joint Venture
- **Conrad Christensen,** Principal/Founder, Christensen Materials Engineering

12. List of Key Contractors and Consultants Involved

Alta Vista Solutions Provider of structural material source inspections and quality assurance services for the East Span Replacement Project.

American Bridge/Fluor Joint Venture Contractor for SAS Bridge contract of the East Span Replacement Project.

Bay Area Management Consultants (BAMC) Joint venture of Hatch Mott MacDonald and URS; contractor to BATA to augment staff as necessary to assist in performing their responsibilities and provide technical expertise.

Dyson Corporation Fabricator for the high-strength A354 grade BD rods under the SAS Bridge Contract of the East Span Replacement Project.

Kiewit/FCI/Manson (KFM) Joint venture and contractor for the E2/T1 Marine Foundation Contract of the East Span Replacement Project.

MacTec Engineering and Consulting Provider of structural material source inspections and quality assurance services for the East Span Replacement Project.

Moffatt & Nichol Designer of Record for the new East Span Replacement Project and part of the Design Joint Venture with T.Y. Lin International.

T.Y. Lin International Designer of Record for the new East Span Replacement Project and part of the Design Joint Venture with Moffatt & Nichol.

Vulcan Threaded Products Fabricator for the tower rods for E2/T1 Marine Foundation Contract of the East Span Replacement Project.

13. List of Technical Appendices

Appendix A: BATA Meetings

A.1 3/27/2013 BATA meeting materials

A.2 4/10/2013 BATA Oversight Committee meeting materials

A.3 4/24/2013 BATA meeting materials

A.4 5/8/2013 BATA Oversight Committee meeting materials

A.5 5/29/2013 BATA meeting materials

Appendix B: TBPOC Workshops

B.1 4/17/2013 TBPOC Workshop materials

B.2 5/01/2013 TBPOC Workshop materials

B.3 5/15/2013 Workshop materials

B.4 6/25/2013 Workshop materials

Appendix C: Other Meetings

C.1 4/14/2013 Senate Transportation and Housing Committee Informational Hearing materials

C.2 5/06/2013 Seismic Safety Peer Review Panel Presentation materials

C.3 6/7/2013 A 354BD Bolts Testing and Evaluation meeting materials

Appendix D: Correspondence

D.1 3/29/2013 Caltrans Letter "Bay Bridge E2 Connector Rods"

D.2 TBPOC and FHWA
5/08/2013 Letter from TBPOC to FHWA

D.3 Caltrans and Senate Committee on Transportation and Housing:

5/21/2013 Letter from Caltrans to Senate Committee on Transportation and Housing

5/21/2013 Letter from Senate Committee on Transportation and Housing to Caltrans

5/31/2013 Letter from Caltrans to Senate Committee on Transportation and Housing

D.4 TBPOC and State Senate:
5/30/2013 Letter from Senate Committee on Transportation and Housing to TBPOC

June 2013 Letter from TBPOC to Senate Committee on Transportation and Housing

D.5 California Legislature and TBPOC:

6/10/2013 Letter from California Legislature to TBPOC

6/14/2013 Letter from TBPOC to California Legislature

D.6 4/04/2013 Letter from Professor Thomas Devine, UC Berkeley

D.7 4/21/2013 Report and 5/23/2013 Letter from Yun Chung

D.8 5/16/2013 Letter from Mr. B. Donoghue

Appendix E: A354 grade BD Rods Project Binders

E.1 Item 1- “E2 Shear Key Anchor Rods (2008) — 96 Rods Fabrication and Installation Processes”

E.2 Item 2- “E2 Bearing & Shear Key Anchor Rods (2010) - 192 Rods Fabrication and Installation Processes”

E.3 Item 3 and 4- “3&4 E2 Shear Key & Bearing Anchor Rods (Top) (2009-2010)-320 Shear Key Rods 224 Bearing Rods Fabrication Processes”

E.4 Item 5- “5 E2 Bearing Assembly Anchor Rods (2007-2010) - 96 Rods Fabrication and Installation Processes”

E.5 Item 6-”6 E2 Bearing Retainer Ring Plate Assembly Anchor Bolts (2009-2010) - 336 Rods Fabrication and Installation Processes”

E.6 Item 7- “7 PWS Anchor Rods (2011) - 274 Rods Fabrication and Installation Processes”

E.7 Item 8- “8 Tower Saddle Tie Rods (2010) - 25 Rods Fabrication Process”

E.8 Item 9- “9 Tower Saddle Turned Rods (2010) - 108 Rods Fabrication Process”

E.9 Item 10- “10 Tower Saddle Grillage Anchor Rods (2010-2011) - 90 Rods Fabrication Process”

E.10 Item 11- “11 Tower Outrigger Boom Anchor Rods (2011) - 4 Rods Fabrication Process”

E.11 Item 12 &13 “12&13 Tower Anchor Rods (Type 1 & 2)(2007-2008)-424 Rods Fabrication Process”

E.12 Item 14- “14 East Saddle Anchor Rods (2010) - 32 Rods Fabrication Process”

E.13 Item 15- “15 East Saddle Tie Rods (2010) - 18 Rods Fabrication Process”

E.14 Item 16- “16 Cable Bracket Anchor Rods (2011-2012) - 24 Rods Fabrication Process”

E.15 Item 17- “17 Bikepath Anchor Rods (2007-2009) - 43 Rods Fabrication Process”

E.16 “Department Audit Summaries- Facilities involved with the fabrication of A354 Grade BD anchor rods — SAS Contract”

E.17 SAS A354BD Testing Program Results Tests I, II, and III; June 25, 2013

Appendix F: Design Criteria, Special Provisions, and Bridge Design Specifications

F.1 Self-Anchored Suspension Bridge Design Criteria

F.2 Contract 04-0120F4 Special Provisions and Addenda (SAS Superstructure First Advertisement)

F.3 Contract 04-0120F4 Special Provisions and Addenda (SAS Superstructure Second Advertisement)

F.4 Contract 04-0438U4 Special Provisions and Addenda (RSR)

F.5 Contract 04-0120E4 Special Provisions and Addenda (SAS Marine Foundation)

F.6 Bridge Design Specifications Section 8-Reinforced Concrete

F.7 Bridge Design Specifications Section 10-Structural Steel

Appendix G: ASTM

G.1 A123/A123M - 12 Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products

G.2 A143/A143M - 07 Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement

G.3 A354 - 11 Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners

G.4 A490 - 12 Structural Bolts, Alloy Steel, Heat Treated, 150 ksi Minimum Tensile Strength

G.5 F606 - 11a Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets

G.6 F1470 - 12 Fastener Sampling for Specified Mechanical Properties and Performance Inspection

Appendix H: Other Documents

H.1 Caltrans (5/21/2013) - "Summary Timeline of Decision to Follow National Standards For Bolts Set by American Society for Testing and Materials"

H.2 Caltrans (12/28/2007) - Construction Policy Bulletin "CPB 07-7 Release Procedures for Materials Requiring Fit-for-Purpose Decisions"

H.3 Caltrans (5/30/2013) - "Comparison Graphs (Field Hardness vs. Lab Hardness)"

H.4 TY Lin (5/17/2013) - "ASTM A354BD BOLTS Testing Program"

H.5 ABF (3/11/2013) - "E2 Bearing and Shear Key Erection Plan: Anchor Rod Stressing Anchor Rod Failure Map"

H.6 Dyson (April 2013) - "Customer Presentation"

H.7 BAMC (5/10/2013) - SAS Project NCR List Related to Dyson

H.8 CCO# 91 (10/07/2008 Contract Change Order Memorandum, 10/07/2008 Contract Change Order, 10/31/2008 Authority To Proceed- CCO #91 -Additional Magnetic Particle Testing of Anchor Rods/Bolts, 11/03/2008 Letter to Caltrans: Authority To Proceed CCO #91 Additional Magnetic Particle Testing of Anchor Rods/Bolts Confirmation of Scope Regarding Existing E2 Shear Key Rods, 05/22/2009 RFI 1741R01 CCO 91 Clarification)

H.9 Caltrans (5/11/2013) - "Background on E2-T1 and SAS A354BD Anchor Rods"

H.10 Tennessee Galvanizing (5/29/2013) - Letter on Galvanizing for Vulcan Threaded Products

H.11 Page from Self-Anchored Suspension Bridge Design Criteria (specifying Caltrans Bridge Design Specifications Manual)

H.12 Sole-source Documents (Various)

H.13 "Metallurgical Analysis of Bay Bridge Broken Anchor Rods S1-G1 & S2-A6," May 7, 2013

This report is printed on recycled paper

TOLL BRIDGE PROGRAM
OVERSIGHT COMMITTEE

CALTRANS BAY AREA TOLL AUTHORITY CALIFORNIA TRANSPORTATION COMMISSION

Department of Transportation
Office of the Director
1120 N Street
P.O. Box 942873
Sacramento, CA
94273-0001

web: baybridgeinfo.org