Supplemental 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

December 30, 2014
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 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
Supplemental Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge with Final Findings and Decisions

December 30, 2014

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Preface

This Supplemental Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge by the Toll Bridge Program Oversight Committee (TBPOC) is the culmination of months of investigation, research and testing by dozens of experts in the areas of metallurgy, fasteners, materials, corrosion, inspection and structural engineering.

1. The A354 grade BD high-strength steel rods that were fabricated in 2008, and then failed in 2013 when tensioned to their designed tensile load before the bridge opened to traffic, failed as a result of hydrogen embrittlement. The three conditions necessary for hydrogen embrittlement — susceptible material, a source of hydrogen, and high tensile loads — all were present in this case. Due in part to low toughness, the 96 rods manufactured in 2008 were materially susceptible to hydrogen embrittlement; were designed to be under high sustained tensile loads; and were subjected to environmentally induced hydrogen after having been allowed to be immersed in water.

2. The steel saddle retrofit, completed in December 2013, maintains the design integrity of the bridge by replacing the clamping force that originally was to have been provided by the failed 2008 rods.

3. The remaining A354 grade BD high-strength steel rods used on the bridge can safely remain in service with continued inspection and maintenance. These rods — which were fabricated in 2006, 2010 and 2013 — were fabricated differently, and installed differently, than the 2008 rods. They also exhibit better material properties and many of them are under lower design tensile loads. These rods can remain in service with continued inspection and maintenance, and their integrity will be further enhanced with supplemental moisture barrier systems.

This report supplements the findings and decisions made by the TBPOC in its July 2013 Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge. The complete 2013 report, as well as comprehensive information about the TBPOC’s investigation, including detailed test results and reports, may be found online at www.baybridgeinfo.org.
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Supplemental Report on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge with Final Findings and Decisions

Report Purpose

This supplemental report focuses on the long-term performance of all the A354 grade BD high-strength steel rods (subsequently referred to in this report as “A354 BD rods”) installed on the Self-Anchored Suspension (SAS) Bridge of the new East Span of the San Francisco-Oakland Bay Bridge — excluding the failed 2008 rods that were originally used to connect shear keys S1 and S2 of the SAS Bridge superstructure to Pier E2 but are no longer in service. This report presents the technical analysis, test results and findings of a rigorous testing program to evaluate the suitability of the various types of A354 BD rods used in the SAS Bridge to perform their function during the 150-year design life of the new span. It concludes with the final findings and decisions of the Toll Bridge Program Oversight Committee (TBPOC) to answer and bring closure to the questions about why a portion of the A354 BD rods failed, and what actions are needed for all remaining A354 BD rods on the SAS Bridge.

Taken together, this supplemental report and the TBPOC’s 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) and all technical studies, reports, and extensive technical expert contributions represent the complete investigation into the A354 BD rods on the SAS Bridge and the findings and decisions related to the following three investigative questions:

1. What led to the failure of the A354 BD 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? (Addressed in July 2013 report and constructed later that year)
3. What should be done about the 2,210 other A354 BD rods used elsewhere on the SAS Bridge?

This supplemental report focuses on questions 1 and 3.

Overview

The TBPOC — composed of the executive directors of the California Transportation Commission and the Bay Area Toll Authority, and the director of Caltrans — 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 led the investigation into the fractured A354 BD rods installed on the Self-Anchored Suspension (SAS) Bridge of the new East Span.

When 32 of the 96 A354 grade BD rods used to secure shear keys S1 and S2 to Pier E2 failed in
March 2013 after being tightened to their specified tension levels, the TBPOC sought answers into why these rods failed and whether the 2,210 other A354 BD rods on the SAS Bridge also are at risk. The TBPOC directed its staff and consultants 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 technical analysis, findings and recommendations from the investigation have on the TBPOC’s determination of which parties were responsible for the failure.

On July 8, 2013, the TBPOC issued its original report entitled *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*. This report concluded that the 2008 A354 BD rods failed as a result of hydrogen embrittlement and directed additional investigation and review of the failure and use of all remaining A354 BD rods on the SAS span. On September 30, 2014, this investigation and review was reported on by a team of contributors, including expert metallurgical, fastener and corrosion consultants, T.Y. Lin International/Moffatt & Nichol Design Joint Venture, and Caltrans.

On July 10, 2013, the TBPOC approved the design of the steel saddle retrofit to replace the design strength provided by the failed 2008 rods at Pier E2, thereby keeping with the original design intent of the bridge. With the clamping force now provided by the steel saddle retrofit, on which construction was completed in December 2013 (see Figure 1), the investigative question pertaining to the retrofit strategy has been answered (and thus is not the focus of this supplemental report). On August 15, 2013, the TBPOC determined that it was safe to open the new East Span after replacing the capacity lost by the failed 2008 A354 BD rods with the installation of bearing shims. On September 2, 2013, the new East Span opened to traffic.

**Figure 1** E2 Shear Key Saddle Retrofit Under Construction
Background: A354 Grade BD Rods on the SAS Bridge

The SAS Bridge of the new East Span contains a total of 17 different applications of A354 BD rods at seven different locations, for a total of 2,306 rods.

Table 1 summarizes the location, description and quantity of A354 BD 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 A354 BD rods, 288 3-inch diameter rods are located at 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 rods connect the shear keys and bearings to the top of the E2 pier cap. In addition, there are 544 2-inch and 3-inch rods connecting the shear keys and bearings to the orthotropic box girders (OBGs) above them — see Items #3 and #4 in Table 1. As noted in Table 1, these rods on Pier E2 are at the highest tension levels of any used on the SAS Bridge.

Table 1  A354 Grade BD Rods on the SAS Bridge

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Location</th>
<th>Component</th>
<th>Fabrication Year</th>
<th>Quantity Installed</th>
<th>Diameter (in)</th>
<th>Length (ft)</th>
<th>Tension (Percent of Fu*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top of Pier E2</td>
<td>Shear Key Anchor Rods (2008)</td>
<td>2008</td>
<td>96</td>
<td>3</td>
<td>10-17</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>Top of Pier E2</td>
<td>Bearing &amp; Shear Key Anchor Rods</td>
<td>2010/2013</td>
<td>192</td>
<td>3</td>
<td>22-23</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>Top of Pier E2</td>
<td>Shear Key Rods (top)</td>
<td>2010</td>
<td>320</td>
<td>3</td>
<td>2-4.5</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>Top of Pier E2</td>
<td>Bearing Rods (top)</td>
<td>2010</td>
<td>224</td>
<td>2</td>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>Top of Pier E2</td>
<td>Bearing Assembly</td>
<td>2010</td>
<td>96</td>
<td>1</td>
<td>2.5</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>Top of Pier E2</td>
<td>Bearing Retainer Ring Plate Assembly</td>
<td>2010</td>
<td>336</td>
<td>1</td>
<td>0.2</td>
<td>0.4</td>
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<tr>
<td>7</td>
<td>Top of Tower</td>
<td>Parallel Wire Strand (PWS) Anchor Rods</td>
<td>2010</td>
<td>274</td>
<td>3.5</td>
<td>28-32</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>Top of Tower</td>
<td>Saddle Tie Rods</td>
<td>2010</td>
<td>25</td>
<td>4</td>
<td>6-18</td>
<td>0.7</td>
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<tr>
<td>9</td>
<td>Top of Tower</td>
<td>Saddle Turned Rods</td>
<td>2010</td>
<td>108</td>
<td>3</td>
<td>1.5-2</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>Top of Tower</td>
<td>Saddle Grillage</td>
<td>2010</td>
<td>90</td>
<td>3</td>
<td>1</td>
<td>0.1</td>
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<tr>
<td>11</td>
<td>Top of Tower</td>
<td>Outrigger Boom</td>
<td>2010</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>12</td>
<td>Bottom of Tower</td>
<td>Tower Anchor Rods (Type 1)</td>
<td>2006</td>
<td>388</td>
<td>3</td>
<td>26</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>Bottom of Tower</td>
<td>Tower Anchor Rods (Type 2)</td>
<td>2006</td>
<td>36</td>
<td>4</td>
<td>26</td>
<td>0.4</td>
</tr>
<tr>
<td>14</td>
<td>East Saddles</td>
<td>East Saddle Anchor Rods</td>
<td>2010</td>
<td>32</td>
<td>2</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>15</td>
<td>East Saddles</td>
<td>East Saddle Tie Rods</td>
<td>2010</td>
<td>18</td>
<td>3</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>16</td>
<td>East Cable</td>
<td>Cable Band Anchor Rods</td>
<td>2010</td>
<td>24</td>
<td>3</td>
<td>10-11</td>
<td>0.2</td>
</tr>
<tr>
<td>17</td>
<td>Top of Pier W2</td>
<td>Bikepath Anchor Rods</td>
<td>2010</td>
<td>43</td>
<td>1.2</td>
<td>1.5</td>
<td>N/A**</td>
</tr>
</tbody>
</table>

TOTAL QUANTITY 2,306

*Fu = Design-specified minimum ultimate tensile strength. Numbers rounded to the nearest tenth.

**Details for bike path support frame have been redesigned to not use these anchor rods.
Figure 2  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) A354 BD rods were installed on the lower housing of shear keys S1 and S2 (Item #1 in Table 1) at Pier E2. Dyson Corporation in Ohio fabricated these rods between June 4 and September 6, 2008, and American Bridge/Fluor Joint Venture, the contractor for the SAS Bridge, installed them in October 2008. Figure 3 illustrates Pier E2 and the location of the shear keys, bearings, and their high-strength steel rods.

*Figure 3  Bearings (B1-B4) and Shear Keys (S1-S4) in Pier E2*
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 (see Figure 4). 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 initially were tensioned 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 load of 0.68 Fu. Between March 8 and March 14, 2013, 32 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 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 the A354 BD rods at shear keys S1 and S2 could have fractured.

Subsequently, a metallurgical investigative team composed of Salim Brahimi (consultant to American Bridge/Fluor Joint Venture), Roseme Aguilar (Caltrans metallurgist), and Conrad Christensen (a consultant to Caltrans who is principal/founder of Christensen Materials Engineering) was tasked with examining the cause of the failures of the 2008 A354 BD rods (Item #1 in Table 1).

On April 23, 2013, based on its examination of two of the extracted A354 BD rods, the metallurgical investigation team 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 metallurgical team concluded the following:
1. The A354 BD rods failed due to hydrogen embrittlement (HE), resulting from the applied tensile load and from hydrogen that already was present and available in the steel as the rods 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 a large difference in hardness from center to edge, and high local hardness near the surface. As an additional consequence of the metallurgical condition, the steel exhibits low toughness and marginal ductility. The combination of all these factors made the anchor rods susceptible to HE failure.

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

**Figure 5 Causes of Hydrogen Embrittlement (HE) or Stress Corrosion Cracking (SCC)**

Hydrogen embrittlement / stress corrosion cracking is a 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 5). For the purposes of this report, hydrogen embrittlement and stress corrosion cracking may be used interchangeably.

In the case of the failed 2008 rods, a combination of the decisions made and the actions taken on the design and specifications, fabrication, and construction activities of the rods led to the three conditions required for hydrogen embrittlement.

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1 The September 30, 2014 bolt investigation found that the hydrogen was environmentally induced while the rods were immersed in water.
A. **Susceptible Material** – The 2008 material, as noted in the April 23, 2013 metallurgical report, was inhomogeneous, and when further examined, exhibited high hardness and ultimate strength. Further, these A354 BD rods were hot-dip galvanized, which is known to increase the risk of development of embrittlement if not addressed adequately.

B. **High Tensile Stress** – The design of the SAS Bridge required the 2008 A354 BD rods to be tensioned to 70% of their ultimate capacity.

C. **Presence of Hydrogen** – The 2008 A354 BD rods were designed to be embedded in Pier E2 directly over the E2 columns, which complicated the grouting and drainage of the embedded rods. The investigation confirmed that these rods were exposed to water for an extended period of time within their rod sleeves.

On July 8, 2013, the TBPOC reported that the A354 grade BD rods installed on the lower housing of shear keys S1 and S2 failed due to hydrogen embrittlement, and directed additional investigation and review of the failure and potential impacts on the remaining A354 BD rods on the SAS span. This additional review took place over the following year.
Supplemental Testing Program After July 8, 2013 TBPOC Report

At the direction of the TBPOC, Caltrans undertook a testing program to further examine the cause of failure, and to evaluate the suitability of all other A354 BD rods on the SAS Bridge. This testing program was designed with the guidance of a team of nine preeminent experts in the fields of fasteners, metallurgy and materials science, chemical engineering, fracture mechanics, and hydrogen embrittlement – referred to as the “bolt team.” (A list of the team members is attached as Appendix B.) The testing was designed to:

- Verify that mechanical properties and chemical composition of all types of A354 BD rods used on the bridge were as specified, and evaluate the uniformity of these properties across the various lots;
- Determine the resistance to hydrogen embrittlement/stress corrosion cracking of the rods in use on the bridge;
- Test the failed A354 BD rods manufactured in 2008 using the same testing protocols that were used for the other rods in use on the bridge to ascertain the similarities and differences between the failed rods and other groups of rods; and
- Evaluate the potential for other failures.

On September 30, 2014, this team of expert metallurgical, fastener and corrosion consultants, as well as T.Y. Lin International/Moffatt & Nichol Design Joint Venture and Caltrans, issued a report titled San Francisco-Oakland Bay Bridge Self-Anchored Suspension Bridge Evaluation of the ASTM A354 Grade BD Rods. This report included the following three findings:

1. The review of construction documents revealed that [the Pier E2] rods were exposed to water that had entered the pipe sleeve assemblies enclosing the rods prior to grouting and tensioning. Water also was found in the rod cavities during the in-situ boroscope examinations that followed the removal of a few fractured rods. Accordingly, there is no doubt that the rods were exposed to water at the time of tensioning (see figures 6 and 7). This is significant because water is a source of hydrogen that could cause embrittlement when a rod is tensioned above its critical threshold load.
2. Although not required by specification, Charpy impact toughness tests also were conducted. These tests showed that the toughness of the majority of the remaining rods is within normal ranges for this material. Charpy tests performed on samples of the 2008 rods, however, showed significantly lower toughness values than the 2006 or 2010 rods (See Table 2). Toughness results for 2013 rods to replace those extracted for testing were higher still.

Table 2  Test I, II, III, and III-M Results Summary

<table>
<thead>
<tr>
<th></th>
<th>Summary of Tests I, II, III, and III-M (all rods)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness — Lab (R/2) (HRC)</td>
<td>35</td>
</tr>
<tr>
<td>Hardness — Lab (R/2) (HRC)</td>
<td>35</td>
</tr>
<tr>
<td>Hardness — Lab (Edge) (HRC)</td>
<td>34</td>
</tr>
<tr>
<td>Toughness — CVN (ft-lb)</td>
<td>35</td>
</tr>
<tr>
<td>Full Size Tensile (ksi)</td>
<td>159</td>
</tr>
</tbody>
</table>

3. A comprehensive study of the mechanical and chemical properties of the rods indicates that the greater susceptibility to hydrogen embrittlement of the 2008 rods is correlated with lower toughness. Further testing demonstrates that failures of the 2008 rods occurred as a result of environmentally induced hydrogen embrittlement, and that the 2008 rods would not have failed if they had been protected from water.

The bolt team concluded that all study results indicate that the 2008 rods on Pier E2 failed due to environmentally induced hydrogen embrittlement because they were tensioned above their hydrogen embrittlement threshold while simultaneously immersed in water, which served as the source of hydrogen. The low hydrogen embrittlement threshold of the 2008 rods is likely due to rod fabrication methods specific to these rods. Other A354 BD rods used on the span were fabricated and tested differently (i.e., using a process known as "vacuum degassing" combined with magnetic particle testing), which resulted in rods with...
improved material properties. There is no evidence that hydrogen present in the steel prior to installation or tensioning contributed to the 2008 rod failures.

**Final TBPOC Conclusion to Question 1**

Based on the foregoing investigative results as well as evaluation and input from staff engineers, consultant engineers, peer review and outside interested parties, the TBPOC concludes that the A354 BD rods installed on the lower housing of shear keys S1 and S2 failed due to hydrogen embrittlement with a finding that the hydrogen was externally induced when the rods were left immersed in water. The cause of these failures was a combination of decisions made and actions taken on the design, specification, fabrication and installation of these rods, which led to the three conditions required for hydrogen embrittlement — high tension, material susceptibility and excess hydrogen. As these rods subsequently were taken out of service and their clamping force replaced by the steel saddle retrofit, no further remedial action on the 2008 rods is necessary.
**Question 3:** What should be done about the other 2,210 A354 grade BD high-strength rods used elsewhere on the SAS Bridge?

The A354 BD rods used on the SAS Bridge are at various locations and of varying diameters, lengths and applied tension levels. There are a total of 17 different types of A354 BD rods at seven different locations, for a total of 2,306 rods. The rods generally can be split into three groups:

1. 96 failed lower Pier E2 shear key anchor rods (Item #1) fabricated in 2008 and installed under the SAS Bridge Superstructure contract;
2. 424 tower anchor rods (Items #12 and #13) fabricated and installed under the SAS Bridge Marine Foundation contract; and
3. 1,786 other rods (Items #2 to #11 and #14 to #16) fabricated and installed under the SAS Bridge Superstructure contract. (Refer to Table 1 and Figure 2 for the locations of these rods.)

Because hydrogen embrittlement is a time-dependent phenomenon and also is dependent on the level of sustained tension, the TBPOC determined — based on recommendations from a number of technical experts and direct test results and observation — that the remaining A354 BD rods were not at risk of failure in the manner that the 2008 rods failed. This determination was based on the rods’ ability to hold their sustained design loads since the time they were installed.

As of September 1, 2014, these remaining rods have been installed and tensioned to their design loads for periods ranging from a little over a year to five years, and they show no signs of failure from hydrogen embrittlement. In contrast, approximately 30 percent of the rods in shear keys S1 and S2 failed just three to 10 days after tensioning to their design loads, and more might have failed if that tension level had been maintained.

Accordingly, the TBPOC largely has focused on stress corrosion cracking (SCC) that may occur over the long term. Stress corrosion cracking also 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 BD rods are susceptible to stress corrosion cracking, and, if so, when such cracking may occur. Like hydrogen embrittlement, there are three factors that contribute to stress corrosion cracking — susceptible material, high tensile stress and the presence of hydrogen. Absent any one of these three conditions, stress corrosion cracking will not occur.
Testing Results for the Remaining Rods

The TBPOC tasked a team of expert metallurgical, fastener and corrosion consultants to further investigate the root cause of the failure of the 2008 A354 BD rods and to evaluate the disposition of the remaining similar rods on the bridge. A review team of Federal Highway Administration (FHWA) engineers concurred with this course of action. Additionally, the TBPOC requested the FHWA to conduct an independent review of its strategies for resolution of the use of the A354 BD rods on the project. In August 2013, FHWA issued its *FHWA Review of A 354 Grade BD Bolts Used in the Self-Anchored Suspension Bridge*, which concurred with the TBPOC’s decision to continue inspecting, testing and maintaining the remaining rods while traffic moved to the new bridge. FHWA concurred with the engagement of experts in dealing with the remaining rods.

The bolt team undertook an extensive testing program to further examine the cause of failure of the 2008 A354 BD rods, and to evaluate the suitability of all other A354 BD rods on the SAS Bridge. The team designed a testing program, field-inspected nearly every A354 BD rod on the bridge and performed laboratory chemical and mechanical testing, as well as fracture testing of both test samples and full diameter rods. The testing was designed to:

- Verify that the mechanical properties and chemical composition of all types of the A354 BD rods used on the bridge were as specified, and evaluate the uniformity of these properties across the various lots;
- Determine the resistance to hydrogen embrittlement/stress corrosion cracking of the A354 BD rods in use on the bridge;
- Test the failed 2008 A354 BD rods with the same testing protocols that were used for the other rods in service on the bridge to ascertain the similarities and differences between the failed rods and other groups of rods; and
- Evaluate the potential for other failures.

The testing program was composed of six parts: Test I, Test II and Test III for conventional mechanical properties and chemical composition; and Test IV, Test V and Test VI for time-dependent SCC testing. Tests I, II and III were completed by June 21, 2013. Independent laboratories in Illinois; Texas; and Hayward, Richmond, and San Francisco, California, performed work for Tests II and III. The results from Tests I, II and III validated previous tests of the A354 BD rods’ mechanical properties and categorized each rod by hardness.

**Tests I, II, and III (Mechanical and Chemical Composition Testing)**

Tests I, II and III for the remaining A354 BD rods verified QC/QA test results and confirmed that these rods have low risk for near-term hydrogen embrittlement failures because they exhibit better metallurgical uniformity and superior toughness than do the failed 2008 rods. As noted earlier, the remaining rods have performed successfully under tension for one to five years.
The main results of field and laboratory testing, as noted by the bolt team, are summarized below:

- The results indicate that the rods within a production batch have similar tensile strength and were subjected to similar heat treatment;
- The field hardness readings were verified by a side-by-side comparison with the hardness readings taken with standard laboratory testing equipment;
- Full-diameter and laboratory tests of the rods confirmed that the A354 BD rods remaining in the SAS Bridge meet the strength requirements;
- The chemistry of the A354 BD rods remaining on the SAS Bridge was found to be very uniform, which indicates that SAE 4140 was the base alloy for all rods except the 2013 rods, which conformed to SAE 4340; and
- The 2008 A354 BD rods exhibited lower Charpy V-notch toughness than the samples from other A354 BD rods in the bridge.

An extensive field hardness survey in Test I (using the Rockwell scale in which hardness values are expressed as HRC) confirmed that all rods have hardness values that conform to specified ranges. ASTM F606 and A354 specifications required hardness values at the mid-radius locations to be between 33 and 39 HRC for rods 1/4” to 2 1/2” in diameter and 31 to 39 HRC for rods greater than 2 1/2” in diameter. The field hardness survey measured hardness at multiple additional locations across the diameter of the A354 BD rods in addition to the mid-radius locations required by ASTM. Test results were found to be as expected for large-diameter rods, with lower hardness values at the core due to slower cooling rates and higher values near the edges because of more rapid cooling rates.

The laboratory Test II hardness testing showed that most of the remaining rods were within 3 HRC of the Test I field testing values for hardness, although at a higher end of the range when compared to the field tests. Laboratory-measured hardness values toward the edges of one Item #12 (2006 Tower Anchor Rods) sample did exceed 40 HRC, but when averaged with other laboratory test samples, the rods were within specified values.
Tests IV, V and VI (Time-Dependent Stress Corrosion Cracking Testing)

The September 30, 2014 report from the bolt team focused primarily on the results of the Townsend Test IV and Raymond Test V. These are accelerated stress corrosion cracking tests that were designed to evaluate the risk of stress corrosion cracking. The Gorman Test VI is an extension of the Raymond Test V. Using slower step rates, the Gorman Test VI was proposed to address concern that there may be crack initiation mechanisms that require a longer time than Test V provides to reveal results. Test VI will be completed in March 2015. However, preliminary results are consistent with completed Test IV and V results. These three tests are named after their respective designers — Drs. Townsend, Raymond and Gorman.

Full-diameter testing of A354 BD rods of the diameter and length of rods used on the SAS is not common. As noted in a lesson learned in the August 2013 FHWA report, “While an expensive option... a full-scale test of a fastener encompasses problems into one test, and there is little to argue about in its results leading it to be the ideal check on quality.”

In Test IV, the tensile load is increased very slowly in steps while the test rod is immersed in a corrosive environment (salt water containing 3.5% sodium chloride) until a threshold load level is established for the onset of cracking due to hydrogen embrittlement. The slow rate of loading is essential to detect the effects of hydrogen that requires time for diffusion. The threshold load level at which a rod can remain in service is established by the ASTM Standard F1624 as being one load step below that at which crack propagation is detected.

Test IV rods were tested to failure with the test results shown on Figure 8. Rods were incrementally loaded in 0.05 step increments until failure occurred or until reaching 0.85 of their minimum specified ultimate strength, whichever occurred first. For the safety of testing staff, after reaching 0.85 of their minimum specified ultimate strength, the rods were loaded until failure. The points on the figure indicate the tested failure loads of the test samples, which range from 0.7 to 1.2 of their minimum specified ultimate strength. The horizontal lines on the figure indicate the design loads specified for each rod group, which range from 0.1 to 0.7 of their minimum specified ultimate strength.
The 2008 A354 BD rods failed by hydrogen embrittlement at the same load (0.70 Fu) that resulted in their failure on the SAS, and with the same fracture characteristics. This result provides confirmation that the Townsend Test (Test IV) duplicates the actual performance of these rods. Further, to explore the possibility that hydrogen already present in the steel (internal hydrogen) could have contributed to the failure of the 2008 rods, the test was repeated in air but protected from rain and without exposure to salt water. These tests show a complete absence of hydrogen embrittlement, which demonstrated to the bolt team that the failures of the 2008 rods occurred as a result of environmentally induced hydrogen embrittlement, and that the 2008 rods would not have failed if they were not sitting in water.

All other groups of rods had failure loads of 0.8 Fu or greater, which, based on ASTM Standard F1624, establishes a 0.75 Fu threshold at which A354 BD rods are not susceptible to failure by hydrogen embrittlement. The 0.75 Fu threshold is greater than the design loads of any of the remaining rods on the bridge, even under the worst-case scenario of direct exposure to salt water as was the case in the testing environment.

Further, additional protective actions taken on the rods — including dehumidification, grease caps, grouting and painting — also will limit exposure of the remaining rods to hydrogen. Combined with proper maintenance, these protective measures are expected to ensure that the long-term capacity of the remaining A354 BD rods is greater than 1.0 Fu. This expectation is further supported by the identification of similar galvanized A354 BD rods tensioned to
0.7 Fu on the Hood Canal Bridge in Washington state that have performed satisfactorily for more than six years in a similar marine environment with the use of grease and paint systems.

The Raymond Test V is a slow, rising step-load laboratory bend test for susceptibility to hydrogen embrittlement. It was conducted with two types of small specimens cut from full-size rods. In one type, a pre-crack was introduced into rectangular bars to establish material susceptibility according to fracture mechanics procedures. These results are consistent with previously published tests of pre-cracked specimens of this material. A second type of specimen included the threaded portion of the as-built rod without a pre-crack. Testing these specimens gave results that were consistent with the results of the Townsend Test IV, thus providing independent confirmation of the results obtained with full-diameter rods. The results of Test V corroborate the SCC threshold established in Test IV with full-diameter rods.

**Summary of Bolt Team’s Conclusions and Recommendations**

Based on the testing results, the bolt team concluded and recommended the following for the remaining rods:

- The 2008 A354 BD rods failed in the field due to external hydrogen embrittlement;
- The testing program established a conservative threshold in an aggressive salt water environment equal to 0.75 Fu for all A354 BD rods on the SAS. This threshold is higher than the applied pre-tension loads;
- The A354 BD rods in service on the SAS are safe, as they are not susceptible to SCC at the design loads and conditions, and no reduction in pre-tension is required;
- Galvanized A354 BD rods on the SAS should be protected from exposure to water by having at least one supplemental barrier, in addition to galvanizing, against moisture: dehumidification, paint system, grout, or grease caps. This is expected to ensure that the long-term capacity of A354 BD rods is greater than 1.0 Fu; and
- The A354 BD rods on the SAS should be inspected and maintained per the SAS maintenance manual. The operating and maintenance instructions for the SAS will include requirements that the supplemental corrosion protection features of the A354 BD rods be periodically checked and that they be maintained in a condition that ensures protection of the rods from exposure to aggressive conditions.

**Response to External Reporting on A354BD Rods**

In an unsolicited report submitted to the TBPOC on December 2, 2014, Mr. Yun Chung raised a number of concerns about the bolt team’s September 30, 2014 report. Mr. Chung states that there are some serious concerns regarding the corrosion resistance and long-term safety of anchor rods installed in the SAS. The TBPOC is committed to ensuring that the SAS will perform safely for its full planned service life of 150 years.

For this reason, the TBPOC and the bolt team have carefully evaluated Mr. Chung’s most critical assertion that the margin between the threshold load for occurrence of external hydrogen embrittlement (EHE) of 0.75 Fu (where Fu is the minimum specified tensile strength
of 140 ksi) and the applied load of 0.68 Fu for many Pier E2 anchor rods is insufficient. The bolt team carefully evaluated this concern during the course of the test program, and concluded that the margin is satisfactory for the following reasons:

- ASTM Standard F1624, which provides guidance for how rising step load tests should be conducted to determine threshold loads for hydrogen embrittlement, states that the threshold is set at one load step below that at which crack propagation is detected. This is the method by which the threshold was determined for the E2 rods, since cracking was detected at a load of 0.8 Fu but not at 0.75 Fu.

- The margin between the threshold load for cracking, 0.75 Fu, and the applied load of 0.68 Fu is 0.07 Fu. However, the actual margin between the applied load and the load that could cause HE is much larger than 0.07 Fu. This is because of protective actions that have been taken on the rods, especially at the critical threaded areas. These protective actions include use of grease caps and paint for the E2 rods, and dehumidification for some of the other anchor rods. With these protective actions, failure of the rods should not occur until loads of 1.1 Fu or more are reached, providing a margin of 0.4 Fu between applied loads and failure loads.

- Industry experience with anchor rods of the same diameter, material, galvanized coating and 0.7 Fu load have performed satisfactorily for over six years at the Hood Canal Bridge with no in-service failures. The corrosion protection measures employed at this bridge include use of grease and paint, similar to the methods used for the SAS, and have worked well. This experience increases confidence that the corrosion protection measures being used at the SAS will ensure a long failure-free life for the A354 BD rods.

- While the TBPOC has concluded that all the remaining A354 BD rods are safe for continued use, the designer of the bridge also has indicated that the design redundancy and a factor of safety of 1.4 mean that the full complement of remaining E2 rods is not required to meet design requirements during an earthquake. In fact, at each shear key and bearing location, as many as 30 percent of the rods could fail and the remaining fastening capacity would be sufficient to resist expected seismic loads.

- Mr. Chung's recommendation to immediately replace the A354 BD rods was an option considered by the TBPOC, but based on the above considerations, the TBPOC has chosen the option of adding additional corrosion protection to the rods since it is safer for workers, more timely, more cost effective, and, in addition, is consistent with industry experience. However, this does not preclude the replacement of the rods in the future should that be required.

Mr. Chung’s report also discusses concerns about the tower base A354 BD rods possibly failing due to environmental hydrogen embrittlement in the event seawater permeates through the concrete of the footing box. After discovering water at the tower base, Caltrans has extensively
tested the water from a number of tower base rods and has determined that the water is not seawater from the bay. This determination is based on the large difference in salinity of the rod water samples and a bay water sample. The water in the tower base likely is due to rain or wash water that had accumulated during construction before the base area was sealed from the environment. Further, the low tension level of these rods does not make them susceptible to SCC.

Based on the above considerations, the TBPOC concludes that the currently installed E2 A354 BD rods and all other A354 BD rods on the SAS are satisfactory. Combined with the supplemental corrosion protections identified in Table 3, the A354 BD rods will provide for the required high level of resistance to seismic loads called for by the bridge design.
TBPOC Conclusions to Question 3

Based on the findings and recommendations of the bolt team, and after considering input from other contributors and a thorough technical evaluation of any differing conclusions, the TBPOC concludes that the remaining A354 BD rods on the SAS span can remain on the bridge with proper maintenance and, in some cases, application of additional supplementary corrosion protection (see Table 3).

Rod-by-Rod Resolution

Most A354 BD rods already were designed with a supplemental corrosion protection, including dehumidification, painting and grout. At those locations where additional supplemental corrosion protection is still required (Items #3 and #4 are noted in Table 3), a supplemental system such as grease caps or painting will be implemented by summer 2015. Due to a revised design for the bicycle/pedestrian path on the SAS, A354 BD rods will not be used for item #17 as noted in Table 3.
### Table 3  Recommended Rod-by-Rod Resolution

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Location</th>
<th>Component</th>
<th>Replace Before Opening</th>
<th>Construction</th>
<th>As-Built Planned Supplemental Moisture Barrier</th>
<th>As-Built Added Supplemental Moisture Barrier</th>
<th>To-Be-Added Supplemental Moisture Barrier</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Top of Pier E2</td>
<td>Shear Key Anchor Rods (bottom)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not used in revised design</td>
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<tr>
<td>2</td>
<td>Top of Pier E2</td>
<td>Bearing &amp; Shear Key Anchor Rods (bottom)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>Top of Pier E2</td>
<td>Shear Key Rods (top)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grease Caps/ Paint</td>
</tr>
<tr>
<td>4</td>
<td>Top of Pier E2</td>
<td>Bearing Rods (top)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grease Caps/ Paint</td>
</tr>
<tr>
<td>5</td>
<td>Top of Pier E2</td>
<td>Bearing Assembly (bushings)</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Top of Pier E2</td>
<td>Bearing Retainer Ring Plate Assembly</td>
<td></td>
<td></td>
<td>X</td>
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<td></td>
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<tr>
<td>7</td>
<td>Anchorage</td>
<td>PWS Anchor Rods</td>
<td></td>
<td></td>
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<td>8</td>
<td>Top of Tower</td>
<td>Saddle Tie Rods</td>
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<td></td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>9</td>
<td>Top of Tower</td>
<td>Saddle Turned Rods</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>Top of Tower</td>
<td>Saddle Grillage</td>
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<td></td>
<td>X</td>
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<td></td>
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<td>11</td>
<td>Top of Tower</td>
<td>Outrigger Boom</td>
<td></td>
<td></td>
<td>X</td>
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<td></td>
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<tr>
<td>12</td>
<td>Bottom of Tower</td>
<td>Tower Anchor Rods (Type 1)</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>13</td>
<td>Bottom of Tower</td>
<td>Tower Anchor Rods (Type 2)</td>
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<tr>
<td>14</td>
<td>East Saddles</td>
<td>East Saddle Anchor Rods</td>
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</tr>
<tr>
<td>15</td>
<td>East Saddles</td>
<td>East Saddle Tie Rods</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>16</td>
<td>East Cable</td>
<td>Cable Band Anchor Rod</td>
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<td>17</td>
<td>Top of Pier W2</td>
<td>Bike Path Anchor Rods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not used in revised design</td>
</tr>
</tbody>
</table>

**Revised Specifications for Replacement Rods**

In 2013, additional A354 BD rods were purchased to replace the 2010 rods on Pier E2 that had been selected for testing. Caltrans applied supplementary specifications for these rods. These supplementary specifications limit the ultimate tensile strength, require minimum toughness and maximum hardness, and impose a tight tolerance on hardness, which will be measured at small intervals across the diameter, thereby ensuring a homogeneous metallurgical structure. The outcome of these specification requirements for the 2013 rods produced significantly improved toughness as compared to the earlier rods used on the SAS bridge (see Table 2).
**Maintenance Plan**

One of the final tasks of the design team is to prepare Bridge Maintenance and Inspection manuals for the East Span, as each section is completed. Each set of manuals will provide documentation on the design, construction, load ratings, detailed inspection procedures for each major section, 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, in-depth or special inspections and routine maintenance on the East Span structures. Regarding the A354 BD rods, the maintenance plan for these components of the SAS (see Table 1) 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.).

Caltrans began regular ongoing inspections as soon as the new bridge was opened to traffic. Final bridge maintenance manuals are still under development by Caltrans and the bridge designer, T. Y. Lin International / Moffat & Nichol Design Joint Venture. Based on recent experiences with the rods, the TBPOC will direct Caltrans to focus inspections on the remaining A354 BD rods on the bridge, with specific emphasis on the highly tensioned rods at Pier E2 (Items #3 and #4) and lower tensioned but critical PWS (Item #7) and tower anchor rods (Items #12 and #13 in Table 1).

The Bay Area Toll Authority has engaged practicing bridge maintenance engineers from the International Cable Supported Bridge Owners Association (ICSBOA) to perform a maintenance peer review. The ICSBOA engineers come from both domestic and international long-span, cable-support bridges. Their peer review is anticipated to be completed in early 2015, and comments and observations will be incorporated into the maintenance manuals as appropriate.
Water at Base of SAS Tower

In September 2014, Caltrans inspectors observed water at the base of the SAS tower beneath caulking that was placed around the A354 BD tower anchor rods (Items #12 and #13).

- The caulking was placed over grouting that filled the space between the rod and rod sleeve to keep the sleeve space clear of debris and help protect the rods from water. The caulking has been removed around all the rods and more than 90 percent of the rod locations showed signs of moisture between the caulking and grouting. Further, during the investigation, it was determined that some rods were not completely or properly grouted.

- Caltrans has tested the water from a number of rod locations and determined that the water is not seawater from the bay (given the large difference in salinity) and that the water likely is rainwater or wash water that had accumulated during construction before the tower base area was sealed from the environment.

- There is essentially no risk of stress corrosion cracking because these rods are tensioned at a relatively low 0.4 to 0.5 Fu (well below the A354 BD threshold of 0.75 Fu for stress corrosion cracking) and have various levels of supplementary corrosion protection. These include dehumidification within the base of the tower and multiple layers of corrosion protection within the foundation such as a steel outer sleeve and combinations of grout and Denso tape protecting the rods.

- Caltrans and the engineer of record, T. Y. Lin International/Moffat & Nichol Design Joint Venture, are investigating this issue to determine if any corrosion or compromise of the rods’ long-term performance has occurred. As part of this investigation, two A354 BD tower anchor rods have been extracted for confirmation testing.

- Caltrans has directed the contractor to provide an investigation plan to map the extent of deficient grout workmanship and to develop a corrective action plan to insure 100% grouting resolution.

Since the issue of water at the base of the SAS tower does not pose a risk of stress corrosion cracking, the TBPOC finalized this report while the tower base issue is separately resolved.
Toll Bridge Program Oversight Committee Findings

The prior nine findings in the TBPOC's July 8, 2013 report stand as stated with the following exceptions:

1. The 2008 A354 BD rods failed as a result of having a higher than normal material susceptibility to hydrogen embrittlement, and from hydrogen that was induced environmentally when these rods were immersed in water during construction.

2. Based on results from the testing program, a greater susceptibility to hydrogen embrittlement was found to be correlated with lower toughness — a material property that was not addressed in contract specifications or ASTM standards for these rods.

3. Caltrans' materials inspection program should have been more rigorous in evaluating these rods prior to installation, and specifications prescribed should have been enhanced to recognize application of A354 BD rods at high tension in a marine environment. Full-scale testing, including wet testing, should have been considered for these rods. The change to require magnetic particle testing during fabrication should have been required of all rods from the start of the project.

4. Based on results of the testing program, the requirement to galvanize did not appear to significantly increase the risk for hydrogen embrittlement or stress corrosion cracking, as both the non-galvanized and galvanized rods performed similarly during testing.
Appendix A – Review by the Seismic Peer Review Panel

The TBPOC has briefed the Seismic Peer Review Panel regarding its investigative report on the A354 BD rods on the SAS Bridge. The Seismic Peer Review Panel has endorsed the bolt team’s principal conclusions and has provided comments on this report. The Panel 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 also is Professor Emeritus and former Dean 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. Dr. 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) from 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.
Appendix B – Bolt/Metallurgy Specialists (The Bolt Team)

A. HERBERT TOWNSEND JR., Ph.D., P.E.

Ph.D. @ University of Pennsylvania in Material Science and Metallurgical Engineering, 1967

President, Townsend Corrosion Consultants

Expertise in corrosion performance and testing of coated and low-alloy steels for the automotive and construction industries.

B. KARL H. FRANK, Ph.D., P.E.

Ph.D. @ Lehigh University in Civil Engineering, 1971

Professor Emeritus, University of Texas at Austin, Department of Civil, Architectural and Environmental Engineering

Expertise in design and behavior of structural steel bridges, and fracture and fatigue behavior of metal structures.

C. LOUIS RAYMOND, Ph.D., P.E.

Ph.D. @ UC Berkeley in Metallurgy, 1963

President, L. Raymond and Associates

Expertise in failure and life analysis, fracture mechanics, coated alloy steel fasteners, hydrogen embrittlement testing and corrosion.

D. ALAN W. PENSE, Ph.D.

Ph.D. @ Lehigh University, 1962

Professor Emeritus, Lehigh University, Department of Materials Science and Engineering

Expertise in metallurgy, welding, joining and failure analysis of large structures.
E. **SHELDON W. DEAN JR., SC.D., P.E.**

Sc.D. @ Massachusetts Institute of Technology in Chemical Engineering, 1962

President, Dean Corrosion Technology Inc.

Expertise in corrosion engineering, electrochemical corrosion testing and electroplating and surface finishing.

F. **BOB HEIDERSBACH, Ph.D., P.E.**

Ph.D. @ University of Florida in Metallurgical Engineering, 1971

Professor Emeritus, Cal Poly State University, San Luis Obispo

President, Dr. Rust, Inc.

Expertise in metallurgy and corrosion, failure analysis for oil and gas industry, military hardware, and construction.

G. **THOMAS J. LANGILL, Ph.D.**

Ph.D. @ Northwestern University in Material Science and Engineering, 1980

Technical Director at American Galvanizers Association

Expertise in corrosion protection of metals and hot dip galvanizing.

H. **DOUGLAS WILLIAMS, P.E.**

M.S. @ U.C. Berkeley in Material Science and Engineering, 1979

Principal, Douglas E. Williams, P.E.

Expertise in metallurgy, welding, and fabrication and inspection of steel structures.

I. **Jeff Gorman, Ph.D.**

Ph.D. @ California Institute of Technology in Engineering Science, 1968

Consultant at Dominion Engineering, Inc.

Expertise in failure analysis, materials science, metallurgy, fracture mechanics, water chemistry and corrosion of power plants.
Appendix C – References


2. *FHWA Review of the A 354 Grade BD Bolts Used in the Self-Anchored Suspension Bridge* (August 2013)

3. *Technical Review of Design and Construction of New East Span of San Francisco-Oakland Bay Bridge* (Submitted to the California Senate Transportation and Housing Committee) (August 26, 2014)
