A354BD Rods Testing Program

Conclusions and Recommendations

September 30, 2014
Toll Bridge Program Oversight Committee
ASTM A354 Grade BD Rods Across SFOBB-SAS

**COMPONENT**

1. Shear Key Anchor Bolts — Bottom (S1/S2)
2. Shear Key Anchor Bolts — Bottom (S3/S4)
   Pier E2 Bearing Bolts — Bottom Housing (B1, B2, B3, B4)
3. Shear Key Anchor Bolts — Top (S1/S2)
   Shear Key Anchor Bolts — Top (S3/S4)
4. Pier E2 Bearing Bolts — Top Housing
5. Spherical Bearing Bushing, Assembly Bolts
6. Bearing Retainer Ring Plate Assembly Bolts
7. PWS Strand Anchor Rods (Main Cable)
8. Tower Saddle Tie Rods
9. Tower Saddle Turned Rods (8 Splices)
10. Tower Saddle Grillage Bolts
11. Tower Outrigger
12. Tower Anchorage Anchor Bolts (75 Dia. Anchor Bolts)
13. Tower Anchorage Anchor Bolts (100 Dia. Anchor Bolts)
14. East Saddle Anchor Rods
15. East Saddle Tie Rods
16. Cable Bracket Anchor Rods
17. Bicycle Anchor Bolts at Pier W2
A354BD Rods at Pier E2 — Break Locations

Location of Breaks

March 2013

2010 — 24 Rods

2008 — 48 Rods

2010 — 24 Rods
# Testing Program Summary

<table>
<thead>
<tr>
<th>TEST NO.</th>
<th>TEST NAME</th>
<th>TEST PHOTO</th>
<th>TEST PURPOSE AND DESCRIPTION</th>
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<tbody>
<tr>
<td>I</td>
<td>Field Hardness Test (in-situ)</td>
<td><img src="image" alt="Hardness Test" /></td>
<td>Hardness is a factor known to affect the stress corrosion cracking susceptibility of high strength low alloy steels. Therefore, to evaluate stress corrosion cracking susceptibility of the A354 BD rods in service, it is necessary to measure and characterize the hardness of the in-situ rods and bolts. Test I is an in-situ hardness test on all accessible A354 grade BD rods and bolts on the Self Anchored Suspension Span. Measurements were then taken across the rod or bolt diameter using an ultra sonic contact impedance hardness tester. 1. Laboratory hardness is performed as a verification of the field hardness measurements in Test I. 2. Toughness (Charpy V-Notch) testing and determining the chemical composition are to characterize the material. The test specimens were either cut from the stick-out of installed rods or they were cut from spare rods that were manufactured in the same lot as the rods being evaluated.</td>
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<tr>
<td>II</td>
<td>Laboratory Tests: Hardness, Charpy, and Chemistry</td>
<td><img src="image" alt="Laboratory Tests" /></td>
<td>This test is to verify the full-diameter tensile capacity of A354BD rods and bolts vs. typical reduced size tensile test results. Full-diameter specimens are tension tested in a laboratory and supplemented by laboratory testing for: reduced size tension test; Rockwell C hardness; toughness (Charpy V-Notch); and chemistry, as well as fracture surface examination and analysis. Test specimens were either extracted from the structure (after analysis confirmed that the capacity of the connections were still acceptable), or from spare rods that were manufactured from the same lot as the rods being evaluated.</td>
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<tr>
<td>III</td>
<td>Full Size Tensile Test</td>
<td><img src="image" alt="Full Size Tensile Test" /></td>
<td>Using full-diameter samples, the stress corrosion cracking thresholds are established for A354BD rods from different material heats and manufactured by different methods. Test IV (Townsend Test) is an accelerated stress corrosion test modeled after the earlier Townsend studies (1975 publication). The testing is as follows: full diameter rods are installed in specially designed and fabricated test rigs that include environmental chambers used to submerge threaded parts of the rod. The applied load is increased incrementally by means of hydraulic jacks and held at each step for 48 hours up to a maximum load of 0.85Fu. In the event the rod does not fail at the maximum applied load (0.85Fu) after being held for 140 hours, the rod is pulled to fracture. Extensive post-fracture testing is performed in laboratory.</td>
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<tr>
<td>IV</td>
<td>Full Diameter Rod Stress Corrosion Test (Townsend Test)</td>
<td><img src="image" alt="Full Diameter Rod Stress Corrosion Test" /></td>
<td>Using small threaded specimens, the stress corrosion cracking thresholds are established using a proven accelerated incremental step load test method for comparison with the Test IV results and for use when larger samples for Test IV are not available. Test V follows ASTM F1624/F2660 protocol that establishes a procedure to measure the susceptibility of steel to hydrogen-induced failures. It does so by measuring the threshold stress intensity factor for the onset of subcritical crack growth using standard fracture mechanics analysis on irregular-shaped specimens such as notched round bars and actual threaded rod specimens.</td>
</tr>
<tr>
<td>V</td>
<td>Small Specimen Stress Corrosion Test (Raymond Test)</td>
<td><img src="image" alt="Small Specimen Stress Corrosion Test" /></td>
<td>This test is to validate the stress intensity factors computed in Test V using very slow step loading rates and a sustained load test. The test includes: (1) A long term (5,000 hours) sustained tests in an environmental chamber similar to Test IV and Test V. The test will be performed at three sustained load levels: (a) at the threshold determined in Test V, (b) at 10% above the threshold, (c) 10% below the threshold. (2) Stepped load testing on Test V size specimens at reduced load rates (halving the threshold rate) to verify the threshold.</td>
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<tr>
<td>VI</td>
<td>Small Specimen Additional Verification Testing @ Reduced Load Rates (Gorman Test)</td>
<td><img src="image" alt="Small Specimen Additional Verification Testing @ Reduced Load Rates" /></td>
<td></td>
</tr>
</tbody>
</table>
Test IV — Townsend Test Results

Test IV (Full Diameter Rod) Test Results (Fu)

Field Measured Rockwell C Hardness (HRC) - Maximum Value Near Edge

- Group 1: E2 2008 Rods (3")
- Group 2: E2 2010 Bottom Rods (3")
- Group 7: PWS 2010 Rods (3.5")
- Group 12: Tower Anchorage 2006 Rods (3")
- Group 18u: E2 2013 Replacement Rods - Ungalvanized (3")
- Group 1: E2 2008 Rods – Dry Test (3")
- Group 4: E2 2010 Top Rods (2")
- Group 8: Tower Tie 2010 Rods (4")
- Group 18: E2 2013 Replacement Rods - Galvanized (3")
Test V — Raymond Test Results

Test V EHE Specimen Fracture Adjusted to Test IV Rod Potential and Test IV Field HRC (Fu-EHE)

Rockwell C Hardness (HRC) - Field Measurement

- Group 2 and 3: E2 2010 Upper Rods (3")
- Group 4: E2 2010 Upper Rods (2")
- Group 8: Tower Tie 2010 Rods (4")
- Group 12: Tower Base 2006 Rods (3")
- IG Fracture Loads
- Pull to Failure Zone for Test IV
- Group 7: PWS 2010 Rods (3.5")
- Test IV Fracture Load
- Reached Limit of 0.85Fu in Test IV
- Rolled Specimen
- Threshold Curve

Applied Loads:
- (E2 Rods)
- (Tower Tie Rods)
- (Tower Base Rods)
- (PWS Rods)
- (Other Rods)
Applied Loads, EHE Thresholds and Rod Capacity with Supplemental Barrier

EHE Threshold, Applied Load and Capacity with Supplemental Barrier

Load as a Fraction of $F_u$

<table>
<thead>
<tr>
<th>Category</th>
<th>Actual Applied Load</th>
<th>EHE Threshold</th>
<th>Capacity with Supplemental Barrier</th>
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</thead>
<tbody>
<tr>
<td>Other Rods</td>
<td>0.10</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>PWS Rods</td>
<td>0.32</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Tower Base Rods</td>
<td>0.48</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Tower Tie Rods</td>
<td>0.68</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>E2 Rods (2008)</td>
<td>0.70</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>E2 Rods (2010)</td>
<td>0.70</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>E2 Rods (2013)</td>
<td>0.70</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Conclusions

- The 2008 rods on E2 failed by EHE because they were tensioned above their HE threshold while simultaneously immersed in water, which served as the source of hydrogen.

- The Townsend Test performed on the 2008 rods in salt solution and in the dry confirmed that without the presence of water, these rods would not have failed.

- All remaining A354BD rods on the SAS exhibit HE thresholds that are higher than their pre-tension stress levels and are safe.

- With the specified supplemental corrosion protection, the capacity of A354BD Rods will be at least 1.0 Fu.
Recommendations

- Nothing further is needed to ensure the integrity of the SAS galvanized A354BD rods that have a supplemental corrosion barrier.

- A supplementary corrosion barrier to the Pier E2 top housing shear key and bearing rods should be provided.

- Application of customary maintenance procedures for the galvanized A354BD rods shall be specified in the SAS Maintenance Manual.
Recommendations (Continued)
The presence of water was recently reported at the bottom of the tower at the shanks of the A354BD anchor rods.

- The source of this water shall be fully investigated and addressed in order to prevent potential long term corrosion.

- This is not a stress corrosion cracking issue, as the rods are pre-tensioned to levels that are lower than their hydrogen embrittlement threshold.
Applied Loads, EHE Thresholds and Rod Capacity with Supplemental Barrier

EHE Threshold, Applied Load and Capacity with Supplemental Barrier

- Load as a Fraction of Fu
- Other Rods: 0.85
- PWS Rods: 0.85
- Tower Base Rods: 0.85
- Tower Tie Rods: 0.68
- E2 Rods (2008): 0.70
- E2 Rods (2010): 0.75
- E2 Rods (2013): 0.70

Actual Applied Load: Light Blue
EHE Threshold: Green
Capacity with Supplemental Barrier: Purple