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Materials Performance Anchor Rod Questions and Responses

Question 1: What is the basis for estimates of the threshold stress for anchor bolt susceptibility to environmental hydrogen embrittlement (EHE), and what is the relationship of this threshold stress to hardness?

Response: The Raymond Test V and the Gorman Test VI, in the Caltrans study confirm the earlier published results of H.E. Townsend[1] for pre-cracked specimens. The Critical Stress Intensity Factor for hydrogen embrittlement (HE)/stress corrosion cracking (SCC) in the presence of a corrosive environment for 4140 steel, Zn-coated or not, occurs in the hardness range from about 32 to 34 HRC. The surface hardness of most of the A354 BD rods and bolts in the SAS Bay Bridge structure are greater than 34 RHC.

It is the representative microstructure/hardness adjacent the cold-rolled threads that will determine the susceptibility of the steel to HE/SCC, assuming the hardness at the R/2 cross-sectional position of the rods is appropriate for only the higher hardenable steel grades or the smaller diameter rods/bolts. The hardness data reported in the various Caltrans reports demonstrate that the near-thread-root hardness is generally higher than the hardness at position R/2 for bolts sized in the 3-4 in diameter range.

An ambiguity concerning the full-scale, Townsend Test IV of the Caltrans study raises questions about the threshold stress for anchor bolt susceptibility to HE/SCC. Consider the following specific example.

In Fig. 8, pg. 16, of the Caltrans report, "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,"[2] the failure loads for full-size, A354 BD Rods tested per HE/SCC conditions (step loaded) are reported. There were four "Group 2" specimens from position E2 in the SAS tested. The Group 2 bottom rods were manufactured in 2010 and are 3-in diameter. Table I, below, lists the failure load as a fraction of the actual specified UTS (based on the RHC data) for these four tests.

Table I - Failure load as a fraction of the actual UTS of the four 2010 manufactured A354 BD Rods

Spec #	RHC	Failure Stress (FS), Ksi	UTS, Ksi	r(FS/F_U)
2a	35	120.4	160	0.75
2b	36	112	165	0.68
2c	37	119	170	0.70
2d	36.4	154	168	0.92

First note that the two of the specimens failed at, or below, 70% of their *actual* UTS. Secondly, note that one of the higher, SCC susceptible rods (RHC = 36.4) did not fail by SCC. This confirms that the full scale testing does not accurately reflect HE/SCC susceptibility. One reason for this is that the rods are not pre-cracked. This test is assessing both crack nucleation and growth. The incubation time for an SCC crack must allow for hydrogen absorption and diffusion; and, even if cracks are present, the crack-tip hydrogen concentration necessary to establish K_{ISCC} might not be established for short-term tests. The accelerated test procedure takes approximately 15 days, insufficient to predict 150-year life. Much plastic deformation occurs in these tests unless an active SCC crack nucleates and grows critical. Additionally, microcracks may be blunted during the loading process, negating assessment of the underlying SCC susceptibility.

It is this author's opinion that the sustained applied tension on the A354 BD rods and bolts on the SAS structure should be lower than $0.7S_U$. Acoustic monitoring, in addition to maintenance of all moisture intrusion barriers, will still be required to assure the design life of the SAS.

Question 2: Is there a distribution of EHE susceptibility (bell curve or other) that corresponds to the distribution of hardness values?

Response: The S_U minimum allowable ultimate tensile strength for this project is 150Ksi. This correlates to a hardness value between 36-37HRC. This lies in the range of HE/SCC susceptibility. In the "SRC Technical Review of Design and Construction of New East Span of San Francisco-Oakland Bay Bridge,"[3] the authors of this independent review suggest the use of a different type of high-strength steel, ASTM F1554, as a more common and appropriate selection for anchor bolts due to better ductility, better ability to be bent and greater suitability for galvanizing. It is a lower strength option. However, the December 2014 Caltrans report[2] states: "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." Perhaps in retrospect the lower strength, ASTM F1554 bolts would have been a better choice for the SAS, as the HE/SCC susceptibility would be a non-issue. Future projects of this nature should consider this viewpoint.

Question 5: Is it critical for bolt galvanizing to remain intact for long-term corrosion protection, and is it reasonable to expect galvanizing to remain intact for the 150-year design life?

Response: Caltrans has stated the following position regarding protective actions that have been taken on the rods [including the use of grease and paint], especially at the critical threaded areas: "… the corrosion protection measure being used at the SAS will ensure a long, failure-free life for the A354 BD rods." Recent events such as the failed rod reported in June 2015,[4] and the evidence of microcracking in the root of the cold-rolled threads require a re-evaluation of this position. It is simply not probable that the environmental and humidity-control measures can be sustained for the 150-year design life of the SAS. One can guard against general corrosion with protective coatings and grease; it is another matter to try to protect a coastal structure from HE/SCC using these methods.

There is no substantiation for the conclusion that "these hydrogen embrittlement susceptible ASTM A354 rods will be fine in the 150 year life of the bridge as it is based on the assumption that the metallic surfaces will be protected from sea water exposure." Caltrans could not assure this protection in the first year and one-half of the life of the bridge; how can they rely on this assumption for 150 years?

Question 6: Is it possible to apply proper maintenance measures (grout, grease, paint) for anchor bolts that are submerged in water intrusions from the bay?

Response: May 2015 water tests indicate the bay water intrusion in various locations throughout the bridge. Bay water is sufficient to meet the environmental requirement for SCC.

In the *Materials Performance* article,[5] water analysis data are presented in Table 2, page 55. This represents one sample and reflects chemistry after five years of possible immersion pre-tensioning, rod failure, and subsequent rod removal. Nevertheless, it suggests a legitimate concern: the effect of high-pH water on stress corrosion cracking of galvanized A354 BD bolts and rods. In "SRC Technical Review of the Construction of the New East Span of San Francisco-Oakland Bay Bridge,"[3] the authors state that under some conditions, the galvanized coating could become reactive with its environment and produce hydrogen as a result. This is true in alkaline environments such as those that may develop in cement-containing structures where moisture is a factor. This is why galvanized pre-stressing strands are not used in contact with cement grout in current U.S. practice. Research to evaluate the rate of absorption of hydrogen into galvanized and bare 4140 and 4340 coupons as a function of alkaline exposures is suggested to gain a better understanding of the hydrogen absorption behavior.

The above scenario, however, in no way indicates that high pH alkalinity is essential to promote HE/SCC in ASTM 4140 (& 4340) steel. The H.E. Townsend paper,[1] demonstrates the role of the zinc coating in the 4140 specimens tested in a saline solution. Galvanization promotes the ingress of hydrogen. Any environmental factor which delays the recombination of surface-adsorbed hydrogen atoms in electrochemical processes increases the probability of absorption of hydrogen into the underlying steel and thus increases the probability of active SCC. Poisoning of the hydrogen recombination reaction may also occur under high pH, alkaline conditions.

Question 7: What is the significance of the microcracks that were discovered in all of the recently-examined bolts?

Response: Caltans reports the presence of microcracks in the roots of cold-rolled threads. One photomicrograph (Item 5d2 of the SAS Tower Anchor Rod Investigation Update[4]) shows one such crack, approximately 12 micrometers in length. However, the crack clearly extends through the zinc surface coating, resulting in a longer effective crack size. Nucleation of a crack has occurred under sustained tensile loading of severely-deformed and thus embrittled steel at the root of the rolled thread. A crevice has been created where environmental conditions may vary greatly from surface conditions. The crevice conditions will most certainly promote the entry of hydrogen into the steel, and the stress concentration at the tip of the crack will drive the accumulation of absorbed hydrogen. Assuming that the applied loads are sufficient, necessary conditions for time-dependent crack extension by the SCC mechanism will be met.

Now the question becomes, are the applied loads sufficient to promote SCC? The current design criteria are based on S_u, the minimum specified ultimate tensile strength. This works well for uniformly loaded structures. However, the rods and bolts are threaded; and, as has been shown, at the root of the cold-rolled threads, one must assume the presence of micro-cracks. For life-prediction, one must transition to a fracture mechanics approach. K_{ISCC}, the Mode I, threshold stress intensity factor for stress corrosion crack growth, is a key parameter to predict usable life. When the local K_I, the Mode I stress intensity factor, meets or exceeds K_{ISCC}, crack time-dependent crack extension will occur.

The applied stress, combined with geometric factors and crack length, determine K_I. However, crack extension may alternatively occur under cyclic loading conditions. As examples, wind and wave loading, minor seismic activity, and normal traffic patterns will impose cyclic loading on the structure; and cyclic fatigue crack propagation might result. Remember, the cracks are already nucleated. As the crack grows, the effective K_I crack-tip stress intensity might increase and approach K_{ISCC}. In this event, the crack growth may switch from fatigue crack growth to the stress-corrosion cracking mode.

In the transportation, energy, and particularly in the aerospace industries, fail-safe design criteria have evolved as materials technology has advanced. As lighter, stronger civil engineering structures are being created, advanced materials will also be called upon to perform. As we push this envelope, design rules and practices must be adjusted accordingly. The lessons learned regarding fatigue, stress corrosion, and other intrusive failure mechanisms must be incorporated in the materials selection and life prediction models for civil engineering structures.

There are two points to be made regarding the hot-dip galvanizing of the A354 BD Rods. One deals with the increased exchange current density when there is a holiday in the Zn coating (i.e., when the Zn and the Fe are in electrical contact within a salt or seawater environment). The second deals with varying concentration and electrochemical conditions within a high-aspect ratio crevice (threaded rod) or crack. Consider the following:

The exchange current density for Fe in a 3% NaCl in an aerated water solution is about 20 $\mu A/cm^2$ at a rest potential of -0.6 V vs. a saturated calomel electrode (SCE). That of Zn in the same solution is about $10 \mu A/cm^2$ at a rest potential of -1.1 V vs. SCE. Thus, a coupon of Zn in an aerated salt solution has about the same exchange current density as a coupon of iron. However, their rest potentials are very different.

If Zn and Fe coupons are put in electrical contact in a salt or seawater solution, the contact potential is intermediate to the two values reported above; and the exchange current density jumps to $200 \mu A/cm^2$. This is a significant current exchange; and, of course, depending on the participating reactions, significant hydrogen generation can occur. This all depends on how much the recombination of adsorbed hydrogen atoms is helped or hindered. Some of the hydrogen will evolve as gas bubbles and some will not recombine, and then the hydrogen might absorb into the steel. A “holiday” on a zinc-coated steel specimen exposed to seawater creates this condition.

External conditions do not necessarily determine the hydrogen uptake of a galvanized AISI 4140 rod; and clearly conditions in a crevice or crack may activate the SCC mechanism.

Question 8: Are there any long-term corrosion concerns that are not related to hydrogen?

Response: High pH conditions developing in restricted regions of the rods/bolts can cause concentration cells to form; then even localized corrosion (and the concomitant metal loss) might become an issue.

Question 9: An article in the June *MP* postulated a failure mechanism involving exposure of the rods to high pH water in the top hats during the interval between grouting and pre-tensioning. Are there any comments on that possibility?

Response: See the discussion of this possibility in the response to Question 6.

References:

1 H.E. Townsend, “Effects of Zinc Coatings on Stress Corrosion Cracking and Hydrogen Embrittlement of Low Alloy Steel,” *Metallurgical Transaction* 6A, April (1975): pp. 877-883.

2 S. Heminger, M. Dougherty, A. Boutros, “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,” Toll Bridge Program Oversight Committee (TBPOC) Report, December 30, 2014.

3 J. Baker, R. DesRoches, R. Gilbert, Y. Hashash, R. Leon, S. Kumarascena, “SRC Technical Review of Design and Construction of New East Span of San Francisco-Oakland Bay Bridge,” July 31, 2014.

4 S. Heminger, M. Dougherty, A. Boutros, “Supplemental Packet on the A354 Grade BD High-Strength Steel Rods on the New East Span of the San Francisco-Oakland Bay Bridge- SAS Tower Anchor Rod Investigation Update (Item 5d2),” Toll Bridge Program Oversight Committee (TBPOC) Report, June 23, 2015.

5 J.A. Gorman, D. Gross, T.S. Hall, S. Matty, S. Christoffersen, A. Cavendish-Tribe, R. Shulock, “San Francisco-Oakland Bay Bridge Anchor Rod Cracking Issues,” *MP* 54, 6 (2015): p. 52.

Bibliography

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Jones, D. A. *Principles and Prevention of Corrosion,* 2nd edition. Upper Saddle River, NJ: Prentice Hall, 1995, Figs. 6.17 and 6.18.