# Herbert E. Townsend

## *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?

EHE thresholds were determined by use of slowly increasing step-load tests in 3.5% sodium chloride solution, based on the work that I published in 1975 (H. E. Townsend, Jr., “Effects of Zinc Coatings on the Stress Corrosion Cracking and Hydrogen Embrittlement of Low-Alloy Steel,” *Metallurgical Transactions A*, 6A, [1975]: pp. 877-883). These tests were conducted on full-size anchor rods representing various locations on the bridge. They provided reliable, conservative values of the EHE threshold. The results clearly show that the preload tensions of all remaining rods are safely below the EHE thresholds determined in our tests, as summarized in Figure 1.

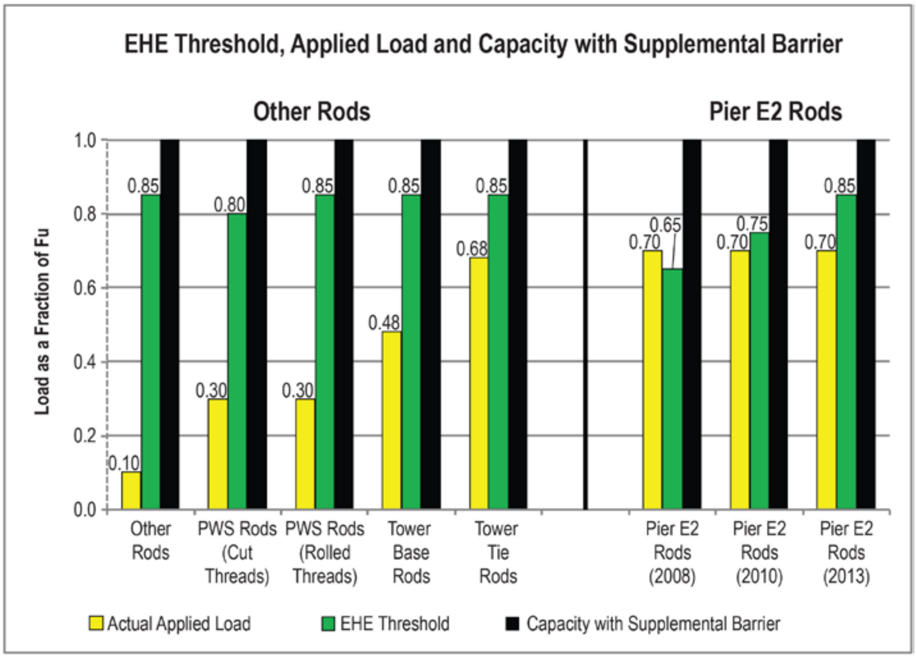

Figure 1. Summary of EHE Testing of Full-Diameter ASTM A354 BD Anchor Rods. (Note that 1.0 Fu = 140 ksi). This figure shows clearly that the service loads are less than the EHE threshold for all rods except for the 2008 rods, which failed on Pier E2. (Reference: H. E. Townsend, K. H. Frank, B. Brignano, and C. Choi, “Hydrogen Embrittlement Testing and Results of Full-Size ASTM A354 Grade BD Rods in the SFOBB,” to be published in *Bridge Structures: Assessment, Design, and Construction*, Khaled M. Mahamoud, Editor, IOS Press, Amsterdam, The Netherlands. These results are also posted online at: http://baybridgeinfo.org/sites/default/files/pdf/SFOBB-SAS%20Evaluation%20of%20the%20A354BD%20Rods%20Final%20Report_0.pdf)

In particular, the 0.48 Fu preload tension in the tower-base rods is well below the EHE threshold of 0.85 Fu as determined by our tests; it can be concluded that these rods will not fail by EHE in the near term. This conclusion is in agreement with the real-world performance of the tower-base rods, some of which have been immersed water for several years at 0.48 Fu without failure. Of course, measures are needed to remove the water and protect the rods from future exposure to water in order to prevent corrosion for the life of the bridge.

For the 2008 rods, our tests found an EHE threshold of 0.65 Fu.  This result is also in agreement with the real-world behavior of the 2008 rods at the Pier E2 (shear keys S1 and S2), which failed within days of being loaded to 0.70 Fu, but did not fail when the loads were reduced to 0.45 Fu.

It is important also to note that our tests reproduced the macroscopic and microscopic appearance of the 2008 rod failures at E2, see Figure 2.

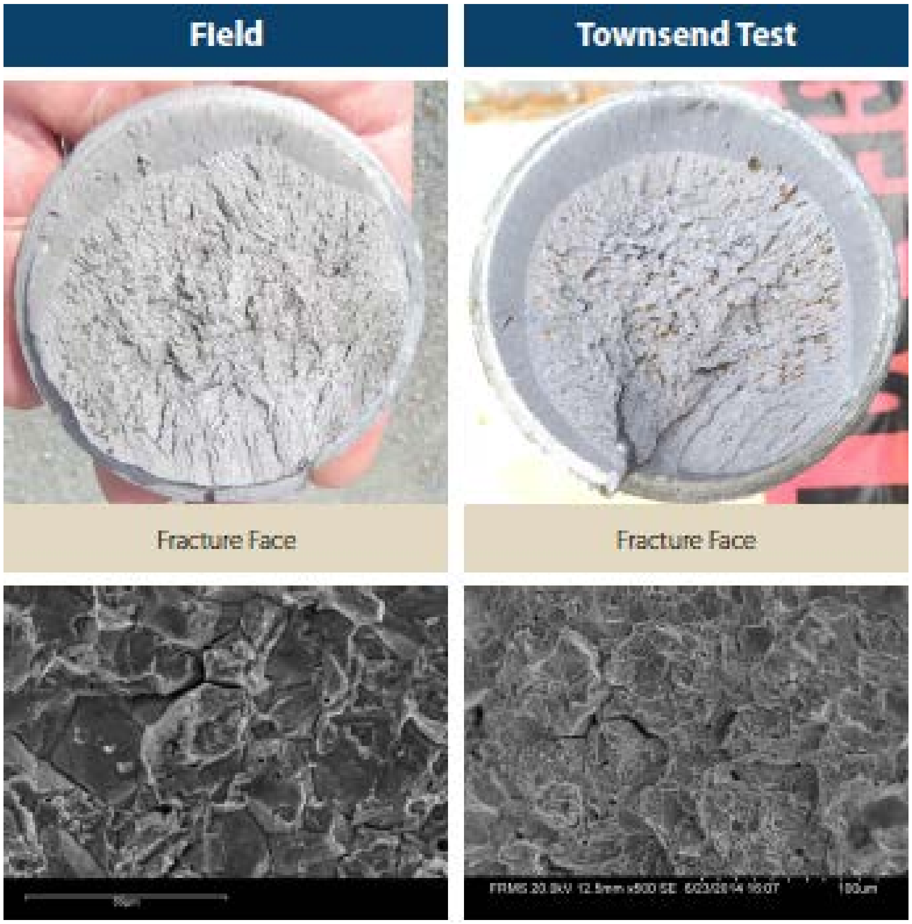

Figure 2.  Comparison of the Fracture Surfaces of the 2008 Anchor Rods, Real-World vs. Test.

Considerations in the design of the full-size rod tests included the loading rate. This is an important factor because if the load rate is too fast, a true threshold may not result. For this reason, the load rate chosen is slower than the rates in my 1975 research by a factor of roughly 2, and slower than the rates found to be adequate in Test V by a factor of 10. The effect of specimen size on hydrogen diffusion is not considered to be important because (in the case of EHE) the critical distance for hydrogen diffusion is measured from the tip of a crack to the region of maximum stress a few millimeters ahead of the crack tip, regardless of the size of the specimen.

Another consideration in the test design was to end the test if EHE was not detected after holding for 6 days at a maximum load of 0.85 Fu. This maximum provided a margin of safety for workers conducting the tests. As a practical matter, there was no reason to go to higher loads because none of the rods on this bridge are loaded above 0.70 Fu. However, this maximum also means that it was not possible to determine differences among rods having EHE thresholds greater than 0.85Fu.

With regard to the effect of hardness, it is well established that EHE thresholds for the quenched and tempered 4140 steel decrease with increasing hardness, as I showed in 1975. (H. E. Townsend, Jr., "Effects of Zinc Coatings on the Stress Corrosion Cracking and Hydrogen Embrittlement of Low-Alloy Steel," *Metallurgical Transactions A*, 6A, (1975) 877-883). If all other material variables are constant as they were in my 1975 research, then hardness would be the lone indicator of EHE susceptibility. However, as shown in the results of the full scale-tests, other variables have a major influence on the EHE thresholds of full-size rods, including: 1) rolling vs. cut threads, 2) toughness as measured in Charpy impact tests, and 3) electrode potential of the galvanized coatings

It is also important to note that the large-diameter rods in our full-scale tests made from quenched-and-tempered AISI 4140 steel typically exhibit significant hardness variations from center to edge. These variations occur because the hardenability of the alloy is insufficient to produce a uniform hardness in 3-inch-diameter rods. The resulting non-uniformity makes it difficult to assign a single hardness value to a particular rod. In terms of average hardness, the variation among our test rods is too small to see a strong effect of hardness on EHE threshold. This contrasts with my 1975 work that was conducted with 1-inch square 4140 bars, which are small enough to harden uniformly from center to edge.

It is very significant that the EHE thresholds were found to be higher for rods exhibiting lower hardness at the outer surface. Lower surface hardness is a characteristic of rods exhibiting an M-shaped hardness profile, as shown in Figure 3 for tower-base anchor rods. The lower surface hardness of rods with the M-shaped profile was investigated and found to be the result of lower carbon content at the outer surface.

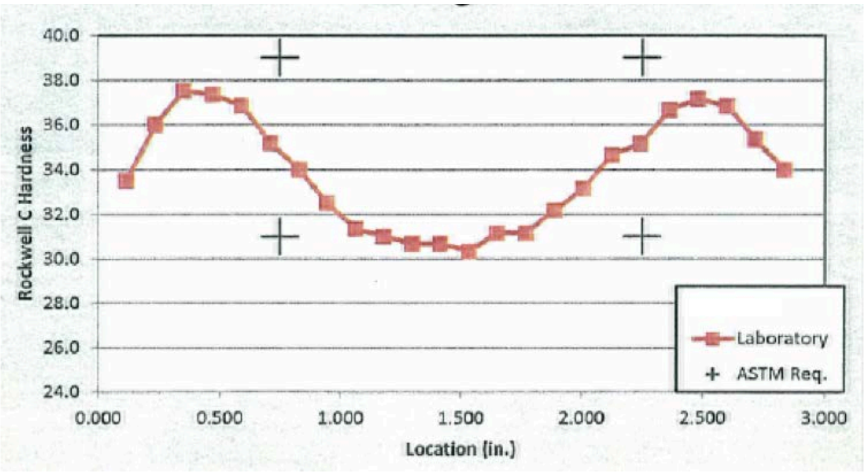

Figure 3. M-shaped Hardness Profile, Showing lower Hardness at Outer Surfaces. This figure represents averages of laboratory and in-situ field hardness of the tower-base rods.

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

It is reasonable to expect a distribution of hardness values among any group of rods made from quenched-and-tempered low–alloy steel. Based on hardness, measurements made in the laboratory, and in the field on almost every rod on the bridge, the actual variation in hardness among rods is remarkably small. Our tests show that EHE thresholds of rods with similar average hardness are significantly affected by other factors, which include: 1) surface hardness (M-shape profiles are beneficial), 2) thread-forming method (rolled threads are better than cut threads), 3) Charpy impact toughness (higher CVN is better), and 4) electrode potential of the hot-dip galvanized coating (less active potentials resulting from higher iron contents lead to higher EHE thresholds).

**Question 3: What is the safety factor for the hardest anchor bolts?**

Factors of safety for each group of rods can be calculated by comparing the heights of the bars in Figure 1 (see response 1). For example, the tower-base anchor rods are loaded to 0.48 Fu, and their EHE threshold is greater than 0.85 Fu. This indicates a safety factor of greater than 1.8 for rods exposed to water, and greater than 2.1 for rods that are dry. These values would not be substantially affected by the observed small variations in average hardness.

**Question 4: Did the additional stresses applied during attempts to achieve tower verticality meet or exceed that safety factor?**

Safety factors were not exceeded as a result of tower alignment. As design engineers for this bridge explain, the tower was erected to a close vertical tolerance. The top of the tower was temporarily pulled back approximately 500 mm during construction. This pull back was necessary to balance the asymmetric weight of free-hanging strands before the load is transferred from the supporting falsework to the cable.

Peak stresses on tower anchor rods due to tower pull back were evaluated and found to be approximately 0.50 Fu for the 3-in diameter rods. This value is only slightly above the design pretension of 0.48 Fu, so it is clear that any effect on the factor of safety is negligible.

It is also noted that prior to pull back, anchor rods were tensioned to their design preload. After load transfer was completed, all rods were re-tensioned, so we know that the rods were intact at that time. A single exception occurred when threads stripped on one of the 424 rods during the re-tensioning procedure. More recently, the rods were again tensioned by loading them to 0.51 Fu and holding for 1 minute. All rods passed this test, with one exception, which was found to be broken and with stripped threads. At the time of this writing, the mechanism of this unusual failure is unresolved, but as Dr. Gorman suggests, it may have resulted from the addition of bending stresses due to partial thread stripping. Two more rods have been removed from the tower base for examination. This leaves 420 of the original 424 rods loaded and intact.

**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?**

It is not reasonable to expect that a galvanized coating will endure for 150 years under wet conditions. To ensure a 150-year life, it is critical the rods be kept dry and protected against corrosion, including general and pitting corrosion.

**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?**

Because the tower rods are loaded well below the EHE threshold, there is no near-term concern about EHE. However, to ensure long-term integrity of the rods, it is essential that measures be taken to avoid corrosion associated with long-term exposure to water. As of this writing several methods, including grease and grout, are being evaluated for this purpose. It is understood that one or more of these methods will be evaluated in full-scale mockup tests prior to implementation on the bridge.

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

Hot-dip galvanized rod coatings on the test rods were found to generally consist of brittle iron-zinc intermetallic compounds. When subjected to tensile stress, these coatings crack, particularly at regions of highest localized stress, such as at thread roots. Depending on such factors as the magnitude of the stress and the toughness of the steel, some of these cracks may extend into the steel substrate for a very short distance to form microcracks. Such microcracks were present on the rods in our EHE tests, and so the EHE thresholds that were measured already take account of the effects of these cracks.

Although the crack in a galvanized coating can be no greater than the thickness of the coating itself, typically about 0.005 inch, the actual length of a crack at a thread root is equal to the sum of the coating thickness plus some fraction of the thread depth. The maximum possible crack length would be the coating thickness plus the entire thread depth. In the case of a 3-inch-diamenter, coarse-threaded rod, this would be equal to 0.005 + 0.136 = 0.141 inch.

According to ASTM E399 (ASTM E399, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials, American Society for Testing and Materials, West Conshohocken, PA. (1997), paragraph 7.1.1.), one of the criteria for plane-strain conditions is that crack length must exceed the value $2.5(K_I/YS)^2$, where $K_I$ is the stress intensity factor, and YS is yield strength.

Using the values of $K_{EHE}$ = 40 KSI-in$^2$, and YS = 140 KSI, the minimum crack length for plane strain is 0.204 in. Thus, the cracks in the galvanized coating do not meet the requirements for plane strain, and one must conclude that the values of $K_{EHE}$ determined by testing fatigue pre-cracked specimens under plane-strain conditions do not apply to threaded rods at the strength level of A354 BD. In the absence of plane-strain conditions, the threshold $K_{EHE}$ will vary according to size and geometry, and will be significantly higher than threshold $K_{EHE}$ values determined under plane-strain conditions.

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

Most certainly! As is the case with any steel structure exposed to a marine environment, ongoing inspection and maintenance will be needed throughout the life of the bridge to avoid the various corrosion issues that may occur. In the case of the Bay Bridge, particular attention should be given to critical load-bearing components, such as the main cables and the main-cable anchor rods.

**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?**

In my opinion**,** such speculation is unnecessary. This question refers to the paper, J. A. Gorman, D. Gross, T. S. Hall, S. Matty, S. Chrostoffersen, A. Cavendish-Tribe, and R. Shulock, "San Francisco-Oakland Bay Bridge Anchor Rod Cracking Issues," *MP* 54, 6, (2015). The postulated failure mechanism is based in part on the analysis of a sample of pH 13 water that was found in the duct of one of the 32 failed shear-key anchor rods on Pier E2. The composition of this sample is consistent with a mixture of rainwater and grout bleed.

Because an intact hot-dip galvanized coating is a very effective barrier against hydrogen diffusion, it is very unlikely that sufficient hydrogen could have entered the steel during the one-month interval between grouting and tensioning. It is far more likely that EHE occurred after the rods were tensioned, causing cracking of the galvanized coating, and allowing entry of hydrogen.

Moreover, prior to grouting, rods were pulled up within the top hat, so that the washers were flush against the bearing plate. This would have made it difficult for grout, which was added from the top of the duct, to penetrate the bearing plate and washer, and enter the top hat. Borescope examination of five top hats after fracture and removal of rods showed that four had incomplete grout penetration.

The critical agent for EHE of the rod material is water, which serves as the source of hydrogen. The test solution chosen for our EHE tests was 3.5% sodium chloride (NaCl) with a pH in the range of 5-6. This was a reasonable choice because this solution is widely used in EHE testing, and the salt increases solution conductivity and promotes the galvanic reaction that produces hydrogen. So, the question really becomes whether a mixture of grout bleed and rainwater with a pH of 13 that was found in one of the Pier E-2 ducts is different from pH 6, 3.5% NaCl in terms of EHE susceptibility. To my knowledge, there are no reports comparing EHE thresholds in these solutions. In the absence of empirical data comparing these environments, the postulated mechanism is very speculative.

In terms of fundamentals, a pH 13 solution is not expected to be more severe in terms of EHE because EHE threshold depends on the activity of hydrogen at the steel surface. Hydrogen activity is determined by the hydrogen overvoltage. As Sheldon Dean has pointed out in his response to this question, hydrogen overvoltage is less for zinc exposed to a cement solution than it is in a pH 6, 3.5% NaCl solution, so we would expect to find a higher EHE threshold in cement or grout solution.