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Materials Performance Anchor Rod Questions and Responses

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

Response: It is well known that the susceptibility to hydrogen embrittlement (HE) is related to the hardness of steels. However, the hardness is only one of several variables that are important in determining the susceptibility of steel to EHE. The environment is crucial. In the absence of aggressive components such as H_2S, the hydrogen overvoltage is probably the most important environmental variable. This variable will be discussed further in the answer to Question 9. In addition, the composition of the steel and its heat treatment history are important. In particular, the sulfur content of the steel is a key variable affecting EHE susceptibility. In the case of the rods used in the San Francisco Bay Bridge, the basis that was determined for these items was the experimental program that was carried out using both full size rod specimens in 3.5% sodium chloride solution. This work proved that the threshold stress was above 0.75 of the minimum tensile strength for the rod alloy (AISI 4140).

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

Response: In order to answer this question it is necessary to define EHE susceptibility in quantitative terms. Let us define this susceptibility as the threshold stress that will cause an intergranular type of crack progression (i.e., cracking along prior austenite grain boundaries) within a defined time period in a fixed environment, and further that the threshold is the highest stress level that that can be sustained without crack formation. In this case, with a homogeneous lot of steel the relationship between hardness and threshold stress will show a monotonic relationship with the threshold stress decreasing as the hardness increases. However, if one examines the process in more detail, there does not appear to be a direct correlation between the hardness and the crack development. Local hard spots in the steel are not more likely to crack than adjacent areas. For example, specimens with rolled threads did not suffer EHE cracking while similar specimens with cut threads did. In this case, the thread rolling process probably introduced localized internal compressive stresses and upset the grain structure of the steel reducing the susceptibility to EHE. However, the hardness of the rolled threads was higher than cut threads so hardness is not the controlling variable. From a statistical point of view, this would suggest a large standard deviation between hardness and EHE threshold, because hardness in not the controlling variable.

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

Response: Safety factors are usually defined as the ratio of the tensile strength to the applied stress. In the case of the anchor rods used for the tower, this ratio is about 2.1. This ratio is based not on the hardest rod, but the minimum tensile strength for the specified metal. For the hardest anchor rod the ratio would be greater, probably around 2.4. However, it should be noted that the concept of a safety factor for these rods is quite different from what would be used for a pressure vessel or structural beam. These rods are intended to be effective during an earthquake of a predetermined magnitude. They are not required for the normal operation of the bridge. Because the frequency of earthquakes reaching the specified magnitude is one in 1,500 years, the probability that the rods would ever be challenged to their required stress level is very low, ant that stress level is below the minimum tensile strength of the rods. As a consequence, the safety factor is very conservative in spite of being lower than the values accepted for other types of service.

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

Response: Not that I am aware.

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: The galvanized coating is one of several measures that were applied to protect the rods. Its primary function was to provide protection in the event of a failure that exposed the rods to water. However, it is not a long term measure for the protection against the damage that water exposure would cause. In the long term, the only solution is to prevent water from contacting the rods continuously. The galvanizing is effective in short to moderate term exposures (i.e., up to 5 to 10 years of water exposure). As long as water is kept away from the rods, the galvanizing will remain intact.

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: Yes. A grout system that is properly formulated and applied such that it neither shrinks nor cracks should provide adequate protection from water intrusion. Such a water intrusion can only occur through cracks in the concrete at the bottom of the platform where the rods ends are located. The grout is contained in steel sleeves that would prevent any water access from the side. The sleeves also would protect the grout from stresses and defects in the concrete. The grout would keep bay water out of the sleeves and maintain a noncorrosive environment around the rods.

Grease application has been used in cable systems successfully. However, there are several issues with grease that must be addressed in order to have the system be effective. Preparation of the cavities to accept the grease is the first issue. Currently, the cavities are long (6 m, [17 ft]) and small diameter (20 to 50 mm, [1 to 2 in]) created by water blasting the grout out of the annular space between the sleeve and the rod. The most important area to protect is at the bottom of the rod where the threaded portion enters the nut. The access to this area is restricted because the rod has a retaining collar above the plate and a narrow gap through the steel plate at the bottom. In cases where bay water has been leaking into the cavity the problem is even more complicated. In addition, the water blasting has left debris in the bottom of the cavities which should be removed before grease can be applied. In some cases, the water blasted hole through the original grout has not opened up all of the cavities in the grout. It may be necessary to remove all of the grout from the annular space before attempting to place grease in the cavity. That process will surely damage the galvanizing and introduce even more debris to the bottom area. The rods were covered with Denso® tape before they were installed and this material will also potentially create problems. The grease might be applied by heating it to a high enough temperature so it is liquefied.

However, if this temperature is above 100 °C (212 °F) there would be a possibility of having a steam explosion if water were present in the hole as the hot grease was introduced into the hole. In most cases the melting temperatures of the soaps that are used is well above this point. If the grease is applied as a gel, its ability to penetrate into the crevices at the bottom of the cavity would be limited, especially if water was present. The problem in this case is that the water or air would have no place to go. If the grease were applied as a spray it would have no ability to keep water out of the cavity and would only serve as a film to protect the steel. Finally, greases are not designed to be effective in long term applications. Commercial greases are composed of soaps formed by reacting fatty acids with metal hydroxides (typically calcium, lithium, aluminum or sodium) and refined petroleum oil to form a gel. Such products can be effective in isolating metal surfaces from water thereby providing protection. However, gels are not stable in long term exposures because the oil tends to polymerize, oxidize, or form gum. The soaps also will tend to crystallize and exude the oil. Shrinkage and hardening will result from these processes. In a long term application, it would be necessary to remove the grease and replace it on a regular schedule (e. g., every 10 or 20 years).

Painting the rods would be a difficult and expensive option. It would be necessary to remove all of the grout and Denso® tape as described above. Some type of surface preparation would also be required to prepare the galvanized surfaces so that good paint adhesion could be achieved. Drying the cavities would also be necessary. Then applying the paint to the surfaces with only 50 mm (2 in) distance between the sleeve and the rod over the 6 m (17 ft) height, without sags and runs would be a challenge for the most creative application specialist. Thereafter, the challenge would be to maintain the coating in the presence of bay water. It might be necessary to add a cathodic protection system for each rod to eliminate attack at the inevitable holidays. In addition, a paint system would surely need to be replaced long before the 150 year design life was achieved. So the painting option is probably not a viable one to consider, although it could be made to work.

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

Response: These cracks have no significance regarding the long term performance of the rods. They are either the result of the thread cutting operation or the result of straining the brittle hot dipped galvanized coating beyond its ductility limit or both. They are present in all similar rods and were present in the test samples that were evaluated to determine the EHE thresholds. Any reduction in performance of the rods from these cracks has been accounted for in the threshold evaluation.

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

Response: Yes. If these rods are exposed to bay water for a long enough time, the galvanized coating will be corroded away, and then the steel will begin to corrode. If this should happen, the steel could corrode at rates between 2 and 5 mpy (50 to 125 µm/yr). This would ultimately prove damaging to the strength of the rods. However, if microbiologically influenced corrosion were to occur the pitting that could result would prove very damaging to the rods in a much shorter period of time.

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 pretensioning. Are there any comments on that possibility?

Response: First, it is important to understand the source of the high pH water. In the manufacture of Portland cement, limestone is calcined along with a variety of other minerals. A portion of the limestone is converted to calcium oxide (CaO), which is then converted to calcium hydroxide [$Ca(OH)_2$], slaked lime, by reaction with water. The slaked lime has limited solubility in water and a saturated solution of this compound has a pH of about 12.5. In order to obtain a higher pH, it is necessary to remove the calcium ions from the solution. Otherwise the hydroxyl ions will precipitate with the calcium. If compounds such as sodium or potassium sulfate are present in the cement, the calcium would precipitate out as calcium sulfate, but the hydroxyl ion concentration would remain the same. Developing a higher pH requires that water be removed from the mixture. This will occur because the setting of the cement involves the formation of hydrates, thereby removing water. Evaporation will also cause this to occur, but that is not likely in the bridge sleeves. The corrosion of zinc in a high pH solution occurs through the formation of zincate ions as shown below.

$$Zn + 2OH^- = ZnO_2^{-2} + H_2 \uparrow$$

This reaction consumes hydroxyl ions which will reduce the pH of the solution. In situations where the ratio of zinc surface area to solution volume is high, the solution will become saturated with zincate ions rapidly; and the corrosion rate will diminish to almost zero. This is the reason galvanized steel is used in concrete applications.

The question of environmental hydrogen embrittlement then becomes related to the hydrogen overvoltage that exists during the corrosion process. If a steel surface is in contact with zinc in a solution at pH 6 and the area ratio is such that the zinc potential dominates the system, as would occur in a micro-crack, the system potential would be approximately at the equilibrium potential for zinc in the solution. According to M. Pourbaix (M. Pourbaix, *Atlas of Electrochemical Equilibria in Aqueous Solutions,* NACE-Cebelcor, NACE International, Houston, TX, 1974, pp. 406-413) the electrode potential will be about -0.940 V vs. a standard hydrogen electrode (SHE) when the zinc ion concentration is 10^{-6} M. The hydrogen overvoltage in this case is about 0.585 V (0.940 – 0.059 x 6.0 = 0.585).

At pH 13, the zinc potential would be about -1.168 V vs. SHE at a zincate concentration above 10^{-4} M. The hydrogen overvoltage is then 0.399 V. Corrosion of the zinc will increase the electrode potential above the -1.168 level because of the polarization which drives the potential in the positive direction. As a result, the hydrogen overvoltage will be lower than the calculated value.

The significance of these calculations is that the hydrogen overvoltage is less in the high pH solution. As a result, these solutions should be less aggressive in causing EHE. The reference cited where EHE was noted in high pH solutions ran the tests with a potentiostat rather than in contact with zinc. As a result the actual potentials were much more negative than would have been observed in a concrete environment with hot dipped galvanized steel. The testing for the Bay Bridge rods was done with the neutral pH solution and therefore is a more aggressive environment relative to grout bleed and, consequently, the threshold values are more conservative.