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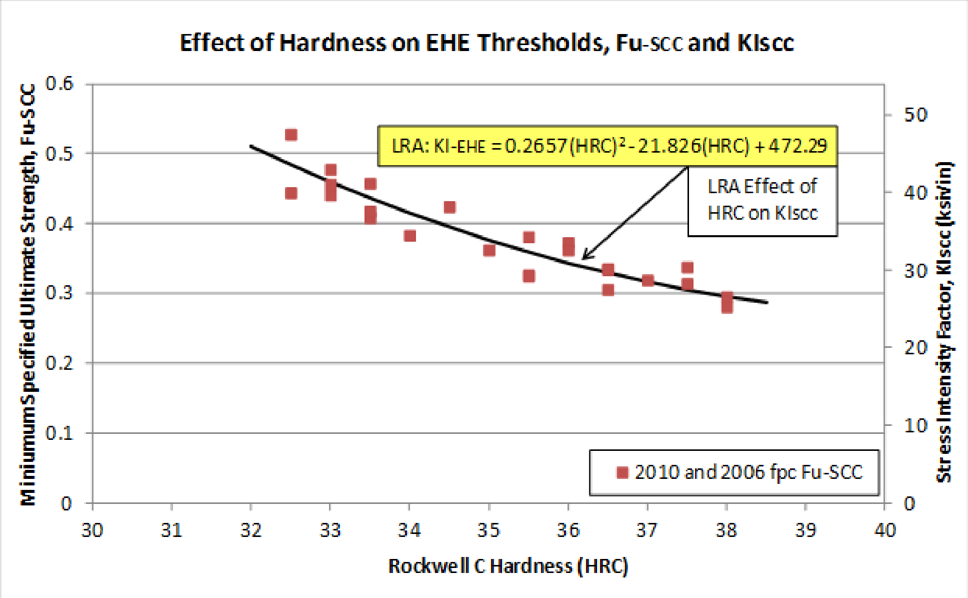
Materials Performance Anchor Rod Questions and Responses

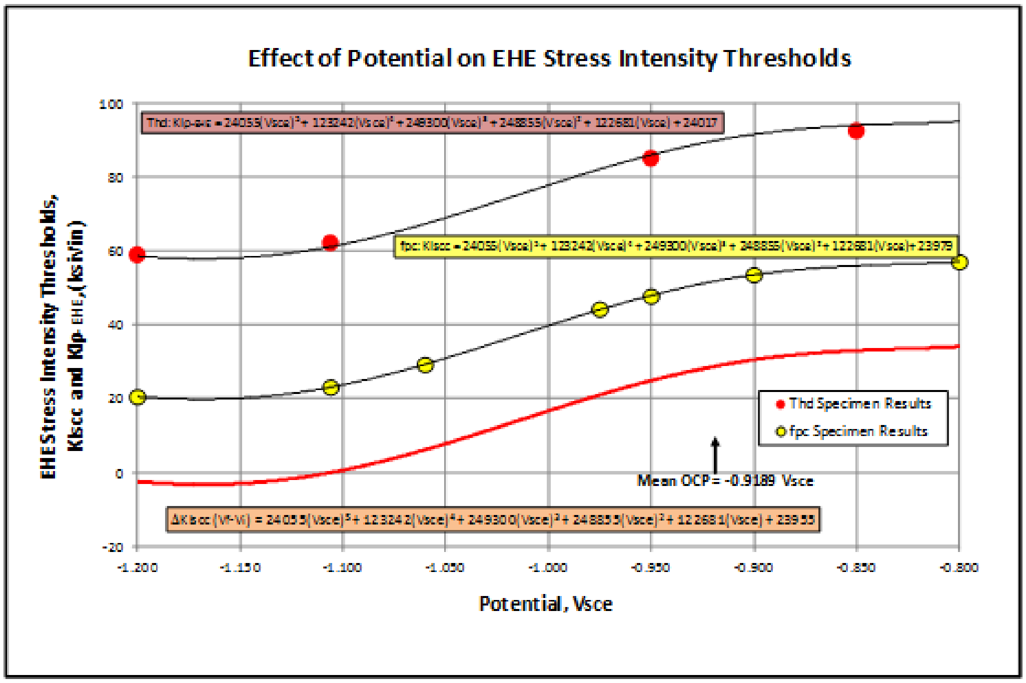
Question 1: What is the basis for estimates of the threshold stress for anchor bolt susceptibility to environmental hydrogen embrittlement (EHE), and what is the relationship of this threshold stress to hardness?

Response: The loads at which full size anchor rods failed due to hydrogen embrittlement (HE) were measured in Test IV. These loads, reported as fractions of Fu, the minimum specified tensile strength, can be converted to stress by multiplying by the minimum specified tensile strength of 140 ksi (965 MPa). As noted in Reference 1.1, the load at which the 2008 anchor rods failed in Test IV was 0.7 Fu, equivalent to a stress of 98 ksi (676 MPa). The minimum load at which any of the other rods failed in Test IV was 0.8 Fu, or a stress of 112 ksi (772 MPa).

As also described in Reference 1.1, the stresses and equivalent loads at which samples of the rod materials cracked due to HE were also measured in Test V using small Charpy size specimens. The Test V results corroborated the Test IV results. In addition, since many more specimens were tested in Test V, they permitted correlations to be developed for several sets of the rods between hardness and the stress required for occurrence of HE. These correlations showed that the stress required for occurrence of HE decreased as hardness increased, and that it also decreased as the potential established by the zinc coating became more negative, as shown in the two figures below.

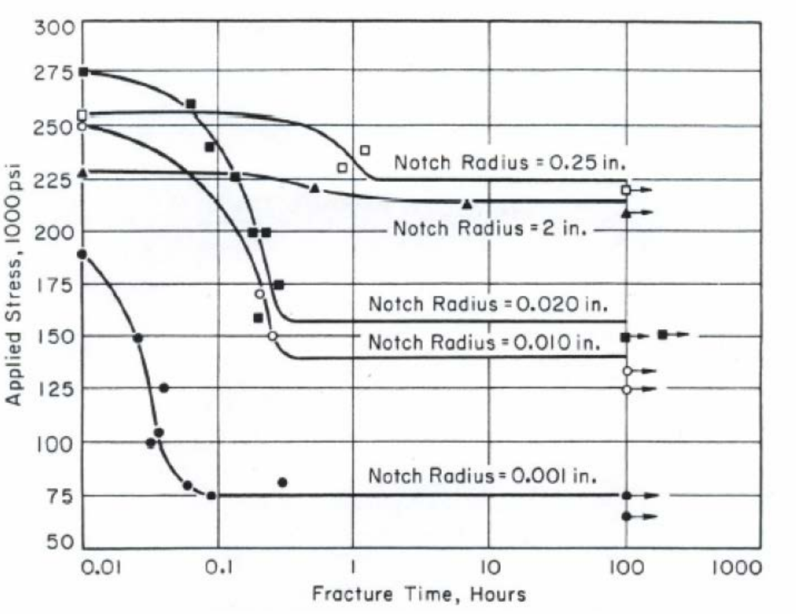


Effect of hardness on EHE threshold force ultimate and stress intensity factor (Ref. 1.2) (Note that this figure is for specimens with fatigue precracks, i.e., for KIscc; the threshold for specimens with thread roots, i.e., KIρ, was about twice as high.)



Effect of OCP on the measured KIscc and KIρ-EHE (Ref. 1.2)

It is also expected that the applied stress required to cause HE will decrease as the stress concentration at the thread root becomes higher. This type of effect has been thoroughly explored as described in Reference 1.2 and shown in the figure below, which presents results of susceptibility to HE as a function of notch root radius. Since the conditions at the root of threads can vary among groups of rods, and between rods in a group, this is another source of variability in the threshold stress for occurrence of HE.



Effect of Notch Root Radius on Delayed Failure Processes in a High-Strength Steel (from Reference 1.3)

Another factor related to the thread root is the possible presence of residual tensile stresses. It is well known that in many material-environment systems the susceptibility to environmentally induced cracking is often more strongly affected by residual stresses than by applied stresses since it is the total tensile stress (applied plus residual) that controls, and since residual stresses in many types of equipment are often higher than applied stresses. While, because of the very high applied stresses in the anchor rod situation, it seems unlikely that stresses will be dominated by residual stresses, it nevertheless seems likely that the total stress will often be significantly impacted by residual stresses from thread forming operations. In this regard, it is well known that high compressive stresses from rolling of threads strongly inhibit stress corrosion cracking (SCC) and HE. It seems possible that tensile stresses from poor thread cutting operations could have the opposite (deleterious) effect.

Another variable affecting the stress or load at which HE occurs is the environment. The tests performed for the SFOBB anchor rods were performed using aerated 3.5% sodium chloride since this environment has been used for many years in tests directed at determining the relative susceptibility of high-strength steels to HE. However, how well this environment models that to which the anchor rods are exposed is not well known. For example, some test data indicate that the high pH deaerated environments that can develop at galvanized steels embedded in concrete can significantly reduce the threshold stresses required for HE (for examples, see references 1.4, 1.5, 1.6 and 1.7). In addition, it is known that deliquescence of the deposited salts that accumulate on surfaces exposed to marine atmospheres can lead to much higher concentrations of chlorides than those of 3.5% NaCl; it seems likely that these high concentrations of chlorides could also affect susceptibility to HE.

In summary, there is no single correlation between hardness and threshold load for HE but rather a distribution depending not only on hardness but also on (1) the potential established by the zinc coating, (2) the stress concentration associated with the radius at the root of the thread, (3) other thread root conditions such as residual tensile or compressive stresses, local cold work, tearing flaws, and microcracks, and (4) the environmental conditions at the highly-stressed area, including pH, potential, concentration of corrodents such as chloride, and availability of oxygen. Considering these many sources of variability, it is important to provide robust corrosion protection measures to protect against the development of environmental conditions that can lead to HE; in other words, it is important to provide corrosion protection methods that keep the metal surfaces of the anchor rods dry.

References for Question 1

1.1 B. Maroney, et al., “San Francisco-Oakland Bay Bridge, Self-Anchored Suspension Bridge, Evaluation of the ASTM A354 Grade BD Rods, Caltrans, Sept. 30, 2014.” Available at baybridgeinfo.org.
1.2 W. Crumly, et al., “ASTM F1624 Rising Step Load (RSL™) Testing for Hydrogen Embrittlement Threshold of Threaded cut outs of A354BD Rods,” *Bridge Structures, Assessment, Design and Construction,* v11,n3,p95-104, 2015.
1.3 M. R. Louthan, Jr. “Hydrogen Embrittlement of Metals: A Primer for the Failure Analyst,” *J Fail. Anal. and Preven*. (2008) 8:289–307.

1.4 W. Zheng and R. Roberge, “Hydrogen Embrittlement in Galvanized Anchor Bars,” *Life Prediction of Corrodible Structures, Proceedings of a Conference,” Kauai, Hawaii, Nov 5-8, 1991*, p65-1 thru 65-15, NACE 1991.
1.5 R. Roberge and W. Zheng, “Hydrogen Embrittlement Susceptibility of Galvanized 4135 Steel in Cement Environment,” *Corrosion Science*, v35n1-4p507-514, 1993.
1.6 F. J. Recio, et al., “Hydrogen embrittlement risk of high strength galvanized steel in contact with alkaline media,” *Corrosion Science*, Volume 53, Issue 9, September 2011, Pages 2853–2860.
1.7 U. Nürnberger, “Hydrogen Induced Cracking of Prestressing Steel in Concrete Constructions – Reasons and Prevention,” *EUROCORR-PROCEEDINGS, 2009*, p. 3958-3968.

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

Response: The answer to the above question is “yes” as shown by a figure in the response to the previous question. It shows how the threshold stress for occurrence of HE in an aerated near neutral 3.5% NaCl solution with an applied potential of -1.106 Vsce varied for the 2010 and 2006 anchor rods. It needs to be kept in mind that this curve can vary from one group of rods to another, depending on factors such as root radius, residual stresses at the root of the thread, etc., as discussed in the response to the previous question

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

Response: This question is difficult to address since the actual environments to which the anchor rods will be exposed are not well defined and can vary between different sets of rods and over time. For the simplistic case where the rods are assumed to be exposed to an aerated 3.5% NaCl solution, the tests indicate that the 2010 set of rods failed at a minimum load of 0.80 Fu, representing a margin of 0.1 Fu above the applied load of 0.7 Fu. However, analyses considering the distribution of hardness and potential developed by the zinc coating indicate that a few of the 2010 rods could fail in this environment at an applied load of 0.7 Fu.

An additional consideration is that, as discussed in the response to Question 1, environments more severe than the test environment of aerated 3.5% NaCl could develop, especially for rods with their lower ends embedded in concrete structures such as the 2008 rods that failed in 2013 and the tower base anchor rods that are currently being investigated.

The main conclusion regarding safety factors is that the only approach that can reliably produce high safety factors against HE is to provide robust corrosion protection measures that ensure that the rods are kept dry (i.e., are protected against being exposed to environments that can produce HE).

An additional observation is that the rods that have highest hardness at the root of the thread are those with rolled threads; because of the compressive residual stresses at the root of the threads, these rods have high resistance to HE.

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

Response: It is understood that the loads applied to achieve tower verticality increased the total load by about 0.05 Fu. Experience to date is that the tower base anchor rods have not experienced HE at their applied loads of 0.37 and 0.48 Fu despite exposure of some of them to in-leaking seawater, nor did they experience HE during the period when the load was increased on some of the rods by the 0.05 Fu increase applied for reasons of tower verticality. The only rod that might have experienced HE is Rod 3, which experienced thread stripping that apparently led to application of non-axisymmetric loads and increased stresses that might have caused HE (further metallurgical examinations are required to determine if the rod actually did fail due to HE) (see Reference 4.1).

Since none of the rods that did not strip threads have failed due to HE, it is concluded that the increased loads applied during the tower vertical straightening operation did not use up the safety factor.

References for Question 4
4.1 M. Lisin, draft report “Review of Tower Rod 3 Fractography Results, Lisin Metallurgical Services Job No. 524-15-003, Preliminary Report,” August 14, 2015.

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: There are two parts to this response:

- If the bolts are kept dry, the condition of the galvanizing will have no effect on HE or SCC since both require moisture to be present on the rod’s metallic surface.
- If the bolts are allowed to become wet, then the condition of the zinc galvanized layer would be a critical factor. In this regard, zinc coatings exposed to marine atmospheres or to seawater generally have life spans of 20 to 50 years. With exposure to corrosive conditions, the zinc coating will eventually lose its protective capabilities such that, even if the load is below the value that can cause HE, general corrosion of the steel could eventually lead to failure of the rod. In addition, as the zinc coating becomes reduced in coverage of the steel, its ability to prevent pitting and possibly active path SCC would be reduced; and the rod might fail due to SCC (e.g., see Reference 5.1). This further demonstrates the importance of corrosion protection to achieve the 150 year life, as also indicated in the first bullet of the answer to this question.

Reference for Question 5
5.1 A. Asphahani' and H. H. Uhlig, "Stress Corrosion Cracking of 4140 High Strength Steel in Aqueous Solutions,” *J. Electrochem. Soc.: Electrochemical Science and Technology* 122, 2, pp. 174-179, February 1975.

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: The answer to this question is that proper corrosion protective measures can protect the rods from contact with seawater and thus prevent occurrence of HE, SCC, and general corrosion. A good example that demonstrates this is experience at the Hood Canal Floating Bridge (see Reference 6.1), where corrosion protection measures involving use of grease and paint have prevented HE and SCC despite the rods being exposed to a much more aggressive marine atmosphere than present at the SFOBB (except for the lower ends of the rods embedded in concrete structures.)

Providing robust corrosion protection measures for the lower end of the tower base anchor rods is under investigation. It appears that the lower ends of some fraction of these rods are currently exposed to in-leaking water from the bay. While this has not led to HE or SCC of rods that have not experienced thread stripping, this exposure to bay water is considered undesirable and could eventually lead to consumption of all of the zinc and to severe general corrosion of the steel. Since this location is below the water level of the bay, providing robust protection against contact with the bay water will require careful design and qualification, which is currently in the planning process.

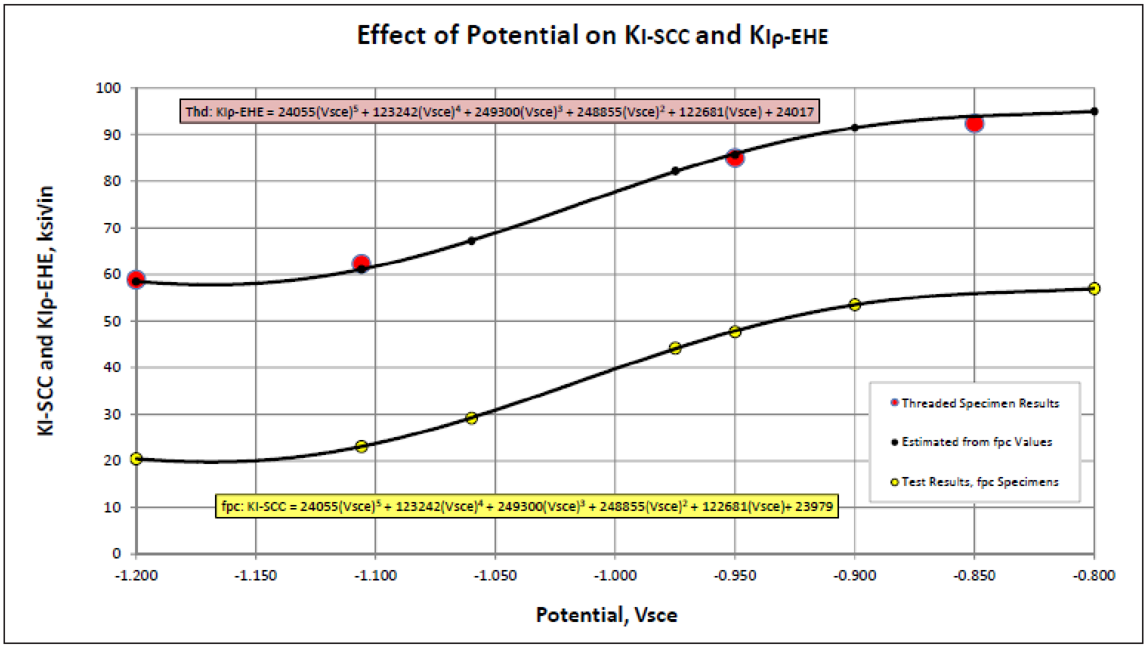
Reference for Question 6:
6.1 R. Shulock, "Hood Canal Floating Bridge High Strength Anchor Bolts Example of Application of Greased and Sheathed Double Corrosion Protection Systems,: Appendix E Sept 30, 2014 final report, available at baybridgeinfo.org.

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

Response: At present, there is no confirmed significant effect of the microcracks since there appear to have been no cases of HE or SCC of tower base rods that have not previously experienced thread stripping. From a hypothetical standpoint, it appears possible that the microcracks could reduce the threshold load for occurrence of HE, based on the following considerations:

- If microcracks are present at the root of the threads in a highly stressed area, such as at the first engaged thread at the lower nut, this could potentially reduce the load required to cause HE by about a factor of two. The basis for this hypothesis is that the presence of a continuous string of microcracks at the root of the thread would make the thread similar from a fracture mechanics standpoint to a fatigue sharpened fatigue crack. As shown by the following figure from Reference 7.1, a sharp pre-crack reduces the load for HE by about a factor of two.

Figure 3.2-12: Effect of Applied Polarization Potential on the Measured KIscc and KIρ-EHE



- The numbers of microcracks observed in the various anchor rods seems to be quite variable. It is speculated that this is a result of differences in the levels of cold work and residual stress in the thread root area, such as caused by differences in tool sharpness and load during thread cutting. These differences could lead to different densities of microcracks developing at different regions of the rods, with the highest density occurring at locations with the highest applied stress (i.e., at the first engaged thread at the nut).
- The number of microcracks could also be influenced by the environment present at the highly-stressed areas.

Regardless of the above scenario, for the loads present on the tower base anchor rods (i.e., 0.47 Fu or less), the microcracks appear to have no effect, since the applied loads and stresses appear to be significantly below the failure threshold level.

Reference for Question 7:
7.1 B. Maroney, et al., “San Francisco-Oakland Bay Bridge, Self-Anchored Suspension Bridge, Evaluation of the ASTM A354 Grade BD Rods, Caltrans, Sept. 30, 2014.” Available at baybridgeinfo.org.

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

Response: Yes, there are two long term corrosion problems that are not related to rapid HE, as follows.

- The first concern is that general corrosion due to exposure to bay water or marine atmospheric environments can result in consumption of most or all of the zinc coating such that it can no longer protect the steel. This is likely to be followed by pitting and general corrosion of the steel until the cross-sectional area of the rod is no longer sufficient to carry the applied load.

- The second concern is that, after the zinc has been largely corroded away, pitting of the steel can occur and lead to active path SCC. This type of mechanism is discussed, for example, in Reference 8.1.

As discussed in the responses to other questions, both of the above corrosion problems can be prevented in the same manner used to protect against HE (i.e., by applying robust corrosion protection measures that keep the metal surfaces of the rods dry).

Reference for Question 8:
8.1 A. Asphahani and H. H. Uhlig, "Stress Corrosion Cracking of 4140 High Strength Steel in Aqueous Solutions," J. Electrochcm. Soc.: Electrochemical Science and Technology, v122,n2,p174-179, February 1975.

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: This question literally applies to the 2008 rods, i.e., the shear key S1/S2 rods that experienced rapid failure after being tensioned in March 2008, since these are the only rods on the bridge with their lower ends in a “top hat.” However, similar environmental conditions can also develop at the bottom ends of the tower base anchor rods since they are dead ended; and there is evidence that water is getting to the lower nut area of these rods. Comments regarding the possibility of the HE of these rods being affected by exposure to high pH water include the following.

- The failure analysis and supporting test results documented by Roberge and Zheng (References 9.1 and 9.2) indicate that high pH conditions were involved in the HE failure of the anchor rods that they studied.
- The research work reported by Recio, et al., and by Nürnberger (References 9.3 and 9.4), among others, indicates that locations where galvanized prestressing steel is in contact with pore water from grout or cement develop high pH and that this increases the rate of corrosion of the zinc coating, increases the rate of hydrogen ingress into the steel, and increases susceptibility of the steel to HE. Most of this work involved tendon wires rather the rods or bolts. While the steel used in tendon wires differs from the steel used for anchor rods, the increase in hydrogen uptake and the increase in susceptibility to HE of the tendon wire steels are considered to indicate that there could be a similar effect of high pH with anchor rod types of steels.

For the tower base anchor rods the higher pH that likely has occurred in the lower nut area could have lowered the threshold for occurrence of HE, in line with the discussion and references noted above. However, it is apparent that the current load levels on the tower base anchor rods are below this reduced threshold since HE failures are not occurring as shown by UT and load tests despite the fact that bay water is reaching the lower nut area of some of the rods. In this regard, it is noted that Rod 3 may have suffered a HE failure; but this was apparently the result of its threads stripping, which resulted in development of high bending induced stresses; this scenario is not believed to apply to any of the other rods.

References for Question 9:
9.1 W. Zheng and R. Roberge, “Hydrogen Embrittlement in Galvanized Anchor Bars,” *Life Prediction of Corrodible Structures, Proceedings of a Conference,” Kauai, Hawaii, Nov 5-8, 1991*, p65-1 thru 65-15, NACE 1991.
9.2 R. Roberge and W. Zheng, “Hydrogen Embrittlement Susceptibility of Galvanized 4135 Steel in Cement Environment,” *Corrosion Science,* v35n1-4p507-514, 1993.
9.3 F. J. Recio, et al., “Hydrogen embrittlement risk of high strength galvanized steel in contact with alkaline media,” *Corrosion Science,* Volume 53, Issue 9, September 2011, Pages 2853–2860.
9.4 U. Nürnberger, “Hydrogen Induced Cracking of Prestressing Steel in Concrete Constructions – Reasons and Prevention,” Eurocorr-Proceedings, 2009, p3958-3968.