

The Susceptibility of Prestressing Strands Within Grouted Post-Tensioned Tendons to Hydrogen Embrittlement: A Review

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ABSTRACT

A preliminary analysis of failed prestressing strands within a post-tensioned tendon on the Wando River bridge in South Carolina showed signs of possible hydrogen embrittlement. One proposed source of hydrogen is through galvanic coupling that may exist between the galvanized steel duct and the steel strands. This coupling, if present, can promote hydrogen evolution at the steel strand's surface which may or may not be mitigated by the condition and quality of the grout. To fully understand the susceptibility of post-tensioned steel strands to hydrogen embrittlement in galvanized steel tendon ducts, the conditions that promote hydrogen production, the kinetics of hydrogen evolution and adsorption into the steel, as well as the subsequent loss of strength need to be well understood.

In an effort to avoid these costly failures in the future, the likely effects of grout quality and the presence of grout deficiencies within galvanized steel ducts will be deduced from prior knowledge of hydrogen embrittlement mechanisms of cold-drawn steels. The focus of the review will be placed on studies and reports that have detailed the kinetics of hydrogen production and adsorption on cold drawn steel strands, and the relationship between stress state and hydrogen content distribution on strength reduction.

Key words: Bridge, Cold-drawn steel, Diffusion, Fracture, Galvanizing, Hydrogen embrittlement, Mechanism, Prestressing failure, Pearlite, Tendon.

INTRODUCTION

Cold-drawn pearlitic steel wire is used to form reinforcing strands in pre and post-tensioned reinforced concrete structures. One particular application of this material is the strands within post-tensioned (PT) bridge tendons. The tendons consist of multiple 7-wire strands contained within a High-density Polyethylene (HDPE) or rigid steel duct. The tendons run continuously through the center of multiple spans of the bridge making contact with spans through concrete deviator blocks which help form the profile of the tendon. Within the concrete deviator blocks and pier segments, the duct is a more rigid material such as galvanized steel. The ends of the tendon are anchored down at bulkheads and stressed after which the duct is filled with cementitious grout [1]. The alkaline grout is intended to provide protection

against corrosion but, due to voids in the grout and/or areas of improper mixing, cases of severe corrosion have occurred.

The corrosion of pre-stressing strands can have disastrous consequences if not detected early. Recently in 2016, a tendon failure on the Wando River bridge in Charleston, South Carolina resulted in subsequent damage of nearby structural components [2]. Metallurgical analysis performed by Applied Technical Services, INC [3] reported that the failure was the result of loss in cross-sectional area and loss in flexibility due to corrosion. The authors stated that moisture ingress must be present to produce the localized corrosion observed. Analysis of the steel strands performed by the University of South Florida showed that some of the failed steel strands exhibited brittle like fracture, possibly the result of hydrogen adsorption. Hydrogen content analysis performed by Luvak Inc. in Boylston, MA reported that some of the steel strands had absorbed as much as 69 ppm of diffusible hydrogen determined by vacuum pressure testing (inactive ASTM E 146-83) indicating that hydrogen embrittlement (HE) could be of concern [4].

Hydrogen is the lightest element and can dissolve in most metals and alloys through interactions with their crystal lattice [5]. Hydrogen atoms may freely move through a metal through the interstices of the crystal lattice or may become trapped at lattice defect sites. The ability of the trapped hydrogen to become released depends on the energy barrier of the defect. Defects with larger energy barriers make it more difficult for the trapped hydrogen to become released [6]. The absorbed hydrogen results in loss in plasticity through mechanisms which are still not fully understood. The loss in plasticity may result in cracks that can result in sudden material failure due to a brittle fracture. One potential source of the hydrogen is hydrolysis of corrosion products resulting in a low pH environment. Another source is excessive cathodic polarization of the high-strength (HS) steel as a possible result of galvanic coupling to the surrounding galvanized steel duct.

For this reason, a review is presented focused on organizing the existing information on the conditions that promote hydrogen production and the mechanisms of hydrogen embrittlement of cold-drawn pearlitic prestressing steels in an effort to determine the implications of grout conditions within galvanized steel ducts to prestressing steel failures. Information from prior failures of prestressing strands possibly the result of hydrogen embrittlement is used to uncover the conditions that may promote hydrogen production in post-tensioned tendons. Hydrogen damage (HD) is used by the European Structural Integrity Society (ESIS) in its TC10 Committee of EAC [7], but since the classical term of HE is common, we also use HE in this report.

PRIOR EVIDENCE OF PRESTRESSING FAILURES DUE TO HYDROGEN EMBRITTLEMENT

A survey of 50 incidents of corrosion of prestressing steel in the United States was published in 1982 [8]. Of those failures, 10 were concluded to be probable cases of SCC, HE, or a combination of both. Most of the failures occurred in post-tensioned structures that were designed to be unbonded or without grout and a loss in ductility was attributed to exposure to an aggressive environment. In 2001, a worldwide survey of the performance of segmental and posttensioned bridges in Europe was performed by the US Federal Highway Administration (FHWA) [9]. Out of 17,612 posttensioned bridges only 2% reported tendon corrosion issues and there was only one mention of hydrogen embrittlement as a potential cause in Norway. Unfortunately, further details were not provided. Outside of the failures reported in these publications, two notable instances are described in detail below. One of the cases is the Berlin Congress Hall which represents one of the earliest known cases and the other a much more recent failure of a tendon on the Wando River Bridge.

BERLIN CONGRESS HALL

One of the earliest reported cases of HE of tendon strands goes back to Berlin Congress Hall in 1980. This structure comprised a double-curved roof made with prestressed concrete construction. Without any detected signs of failure initiation, the southern external roof suddenly collapsed. Based on failure analysis reports, the combined influences of design issues, construction errors, environmental conditions led to its collapse. Today, it is understood that St 145/160 prestressing steel which was used throughout the tendons was very sensitive to stress corrosion cracking (SCC) [10]. This case provides some

indication of the conditions that may promote HE within PT ducts. Wet conditions along with insufficient grouting of the tendons and poor quality concrete promoted hydrogen induced stress corrosion cracking of its tendons [11]. However, hydrogen content analysis of the failed strands was not performed. Interestingly, the strands were coated with a zinc-oxide to prevent corrosion prior to construction.

WANDO RIVER BRIDGE

The James B. Edwards Bridge runs over Wando River located in Charleston, South Carolina and was opened in 1989. A recent failure of one of the post-tensioned tendons occurred at a pier segment within a galvanized steel duct. At that location, the tendon was approximately 80% void of grout. During removal of the failed tendon, it was noted that 5 to 7 strands out of the total 19 strands were corroded [12]. The remaining grout pH was in some locations as low as 5. Metallurgical analysis performed by Applied Technical Services, INC [3] reported that the failure was the result of loss in cross-sectional area and loss in flexibility due to corrosion. The authors stated that moisture ingress must be present to produce the localized corrosion observed. Analysis of the steel strands performed by the University of South Florida showed that some of the failed steel strands exhibited brittle like fracture, possibly the result of hydrogen absorption. Hydrogen content analysis performed by Luvak Inc. in Boylston, MA reported that some of the steel strands had absorbed as much as 69 ppm of diffusible hydrogen determined by vacuum pressure testing (inactive ASTM E 146-83) indicating that hydrogen embrittlement (HE) could be of concern [4]. Whether the hydrogen was produced by galvanic coupling to the galvanized steel duct or through corrosion of the strands themselves requires further analysis.

In each of these failures, voids in the grout and wet conditions led to corrosion of the prestressing steel. In the Berlin Congress Hall case, failure was identified to be a result of hydrogen embrittlement due to the susceptibility of the steel. In the case of the Wando River failure, the corrosion of the strands was likely due to a combination of grout voids and water infiltration that resulted in some cases in brittle failures of the wires potentially enhanced by hydrogen absorption. It is not clear however, what the source of the hydrogen was and why the pH of the grout was so low. In the next sections, the manufacturing processes used to produce the prestressing wires is described as well as the existing knowledge on the mechanisms of hydrogen embrittlement and the relationships between hydrogen adsorption and mechanical properties. Based on the information obtained, the implication of adverse conditions within galvanized steel tendons ducts to PT durability is assessed.

COLD DRAWING OF STEEL WIRES AND ITS EFFECTS ON MICROSTRUCTURE

Pre-stressing strands comprise seven wire high-strength steel strands in which 6 slightly smaller wires are helically wrapped around a single wire. The wires are produced by a cold-drawing process in which the steel is pulled through multiple dies which successively reduces the size of the wires. The drawing process results in significant changes to the material's microstructure and therefore its mechanical properties.

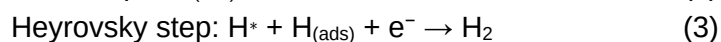
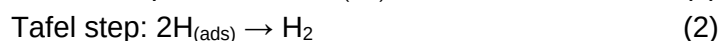
The pre-drawn microstructure of the steel is of eutectoid composition and primarily composed of pearlite grains containing ferrite and cementite lamellae [13]. In general, the pearlite microstructural variations during the drawing process involve: (i) narrowing of the pearlite colonies; (ii) refinement of interlamellar spacing; (iii) and orientation of the lamellae towards the drawing direction. An interlamellar spacing in the range of tens of nanometers can be achieved by wire drawing [14]. The result is a high strength steel with a nanocomposite microstructure (pearlite colonies + pearlitic lamellae) in an oriented direction [15]. However, the general changes in the microstructural features during the drawing process may also be accompanied by site specific irregularities. The initial drawing steps primarily result in grain reorientation while further deformation primarily results in elongation and interlamellar spacing refinement [16]. The grain reorientation does not result in complete alignment of the lamellae and some of the grains are not realigned at all. In the case that the lamellae remain perpendicular to the drawing direction, the lamellae may become more spaced out and begin to kink. Additionally, dissolution of cementite and even breaking of the cementite lamellae can occur. These locations are considered weak points in the steel and are likely initiation sites of fracture.

Another outcome of the drawing process is residual stresses that are unevenly distributed throughout the cross section of the wires with the maximum stress at the surface of the wire. The residual tensile stresses cause the metallic bonds to be elongated resulting in excess space where small hydrogen atoms may diffuse through the steel more easily. If the number of drawing steps is increased, the residual tensile stresses will increase and hence increases the diffusivity of hydrogen atoms [17]. For this reason, the ASTM standard requires a thermo-mechanical treatment step following the drawing process to obtain the desired mechanical properties [18]. Additionally, the residual stress can be partially controlled with the inlet die geometry [17]. The effect of residual stress formed by CD on HE is not considerable in low inlet die angle or high (more than wire radius) bearing lengths. CD with low inlet die angle and long bearing length will show high resistance to HE and therefore longer service life. [19].

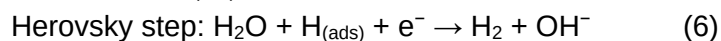
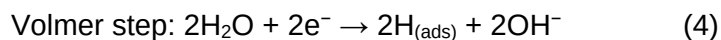
PROPOSED MECHANISMS OF HYDROGEN EMBRITTLEMENT

Johnson reported the decrease in the mechanical properties of metals due to the presence of hydrogen in 1875 [20] yet the mechanisms involved are still under investigation. Generally, there are two types of hydrogen embrittlement (HE). Internal hydrogen embrittlement (IHE) is due to the concentration of pre-existing hydrogen. Hydrogen environment embrittlement (HEE) involves cracking of metals under sustained loads in hydrogen containing environments. Environmental hydrogen embrittlement (EHE) is sometimes used for cathodically protected metals [21]. Heat treatments are the source for internal hydrogen, while external sources of hydrogen may include irradiation, pressurized hydrogen-gas, cathodic protection or corrosion in aqueous solutions. Pre-stressing steels do not have a substantial amount of internal hydrogen and therefore the information presented is focused on HEE in which the hydrogen is the result of the interaction of the steel with the environment.

Hydrogen molecules may be produced by hydrogen evolution as a result of the cathodic processes associated with the corrosion reaction or be driven electrochemically during cathodic polarization [22]. In the first stage of hydrogen evolution, hydrogen atoms adsorb on the metal's surface by discharging of hydrated protons or water splitting. Then, in the second stage, depending on the metal and the current density, the adsorbed hydrogen may desorb and form hydrogen molecules. Only a small amount of the adsorbed hydrogen is usually absorbed by the metal [23]. A summary of the reactions on the metal's surface when it is in contact with acidic solution according to the Volmer, Tafel and Herovskiy routes are:



Whereas, hydrogen evolution in alkaline media proceeds according to the following reactions:



Hydrogen in ferrous metals can be observed in three forms; 1- occupying interstitial sites (since H atom is very small) with a lattice distortion; 2- interacting with defects or adsorbing to the interfaces; 3- molecular hydrogen which forms by the recombination of atomic hydrogen resulting in micro-voids. The first two forms of hydrogen in the metal has high mobility, while the third one will lead to localized stresses. Hydrogen assisted cracking (HAC) is affected by different factors including hydrogen/surface reactions, hydrogen diffusion, and the degradation process of components. The microstructure of a component, temperature and strain rate are also among important studied parameters of HAC resistance [23].

Once hydrogen is absorbed into the metal, it will either diffuse through the lattice through interstitial sites or become trapped by lattice defects. At lower energy trap sites, the hydrogen may subsequently break free and continue to diffuse through the lattice structure. If the barrier energy is high, the hydrogen is said