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New testing method for assessing the cracking sensibility of stressed tendon rods in aggressive environments

Andrés Valiente [a], Mariángel Pérez Guerrero [a,b], Mihaela Iordachescu [a,*]

[a] Materials Science Dpt., E.T.S.I. Caminos, Universidad Politécnica de Madrid, Spain
[b] Facultad de Ingeniería, Universidad de Los Andes, Mérida, Venezuela

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ABSTRACT

The paper presents a new testing method for assessing the cracking sensibility in aggressive environments of tendon rods for prestressed concrete structures, on the basis of Fracture Mechanics concepts. First, it approaches the fundamentals of the designed test in the context of existing fracture specimens, regarding the geometrical limitations introduced by the environmental assisted cracking of the rods, perpendicularly to the load direction. The analysis showed that fatigue precracked chevron-notched short bar specimen (SBS) is providing the largest measurement range of stress intensity factor to be explored in stress-corrosion cracking (SCC) tests. Then, the equation relating the elastic stiffness of SBSs to crack size was experimentally validated for specimens with true cracks produced by fatigue. SCC verification tests were made with an innovative horizontal loading device and the crack mouth opening displacement (CMOD) was acquired and numerically analyzed with a video digital image correlation system. The tests showed that SCC is fully governed by the small scale-yielding regime at the crack tip. Hence, the main process parameters as crack extension and environment-assisted stress intensity factor were empirically obtained for each time sequence of the SCC tests. To simplify further SCC tests instrumentation, an empirical correlation was stated between CMOD and crack opening displacement (COD) as measured by a conventional extensometer mounted on the loading grips of the specimen. This correlation was also validated in the SCC tests.

1. Introduction

The propensity of prestressing steels to general or pitting corrosion is no more a major concern due to the adequacy of the control and protection measurements used today in prestressed construction. However, stress corrosion is still considered their Achilles heel. Stress corrosion appears in specific circumstances, related with improper design and/or construction practices, as well as in contaminated environments [1]. It potentially has catastrophic consequences as prestressing steels are incorporated into critical members whose failure implies the complete collapse of the structure [2–4].

Since the late 1970s, considerable work was conducted to determine the susceptibility of prestressing steel wires and strands to stress corrosion damage [5–7]. This effort is consistent with the serious risk that the phenomenon entails for structural safety, when tendons consisting of bundles of cold drawn eutectoid steel wires or strands are used in pre-tensioned and post-tensioned concrete systems. Today, it is agreed that stress corrosion damage is extremely local, generating only diffuse corrosion products, but it often entails the failure of prestressing steel wire with little elongation and no previous warning [1,2,4].

* Corresponding author.

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Hydrogen embrittlement (HE) and stress corrosion cracking (SCC) are the damage mechanisms that concern the stress corrosion of cold drawn prestressing steels. Two major approaches are used to assess the stress corrosion susceptibility of these steels. The first one is based on accelerated test condition and applied electrochemical potentials [6,8], but it does not give definitive answers about the performance of prestressing steel exposed to realistic aggressive environments. The standardized procedure to assess the hydrogen embrittlement resistance of cold drawn prestressing steel wires consists of measuring the time to failure of a tensile loaded wire sample when immersed in a heated aqueous solution of ammonium thiocyanate [9,10] or in a less aggressive aqueous solution of potassium salts [9]. The second approach is based on Fracture Mechanics concepts and results in more reproducible data on environment assisted cracking of prestressing steels, such as cracking initiation and crack growth rate as a function of stress intensity factor [11]. This involves the use of precracked wire samples [7,12] or of monitoring techniques able to record the occurrence of relevant cracking events, fractographically identifiable [13].

Tendon rod elements made of high strength steels bars were also used in various tensioning systems [14,15], but their susceptibility to stress corrosion cracking was less analyzed in comparison with that of wires and strands due to the temporary nature of most of their structural applications. Nevertheless, in the last two decades, high strength tendon rods presence in permanent structural applications for geotechnical engineering, bridges and buildings construction and/or rehabilitation increased significantly [16]. At the same time, different failure cases of tendon rods were reported [17], and these include stress corrosion failures [18–20]. However, specific procedures to assess the susceptibility to stress corrosion cracking of these rods are hardly developed. ASTM standards for prestressing bars do not address this issue [15]; ISO is basically extending the existing prestressing wires specifications to rods, but only for bar diameters that do not exceed the testing capability of conventional equipment [14,21]. These limitations ask for applying other testing procedures [20] as ASTM F1624 [22], developed by the ASTM Committee F07 on Aerospace and Aircraft.

The paper proposes a new testing method, on a Fracture Mechanics basis, for assessing the cracking sensitivity of stressed tendon rods when exposed to aggressive environments. In this view, the short bar specimens (SBS) of the ASTM Standard E1304 [23] provide an ideal configuration to determine the empirical laws that govern the environmentally assisted cracking of prestressing tendon rods, given the limitations derived from the geometry and the mechanical properties of this construction and building material. However, in contrast with the standardized E1304 procedure, which does not require fatigue precracking, the proposed testing method does use precracked short bar specimens to determine the threshold condition for cracking initiation, as well as the crack propagation rate as a function of the applied stress intensity factor. Thus, the stiffness variation during stress corrosion testing of a precracked SBS is the critical data to be obtained. In the application of the method presented here, stiffness was determined as the quotient between load and crack opening displacement measurements made with conventional and virtual video extensometers.

2. Test design fundamentals

In the Fracture Mechanics approach, stress corrosion cracking (SCC) tests are performed with precracked specimens to determine the crack growth rate, $\dot{a}$, as an empirical function of stress intensity factor, K_I. This function, $\dot{a} = f(K_I)$, is unique over each set of possible combinations given by the material type and environment aggressiveness. Generally, $f(K_I)$ exhibits a vertical asymptote at a threshold value K_{th}. When the applied stress intensity factor surpasses K_{th}, the crack propagation takes place. Hence, the complete characterization of SSC behaviour requires the specimen to be loaded up to values of the stress intensity factor well above the threshold value. This limits the specimen configurations, since the environmentally assisted cracking must occur under small-scale yielding, such as when the stress field at the crack tip is dominated by stress intensity factor. Then, all the above mentioned constrains are highly influencing the design of the SCC tests, especially when dealing with steel products of standardized dimensions, as tendon rods [14,15].

Previously reported SCC failures of steel tendons were due to surface flaws initiated and developed perpendicularly to the applied tensile load [4,18,19]. As a consequence, the SCC tests of tendon rod steels must allow the propagation of a crack contained in the cross section of the rod. Fig. 1 is schematically presenting three known configurations of fracture specimens, as they have to be machined from a tendon rod to obtain the required crack orientation. These are of SBS [23], SE(B) and CT [24] type; only the last two specimens are fatigue precracked. Fig. 2 illustrates the size limitation introduced by the rod diameter in each case, as resulting from their standardized height-to-thickness ratio. Thus, the maximum value K_L of the stress intensity factor compatible with the small scale yielding regime is a function of the specimen thickness, B, and the material yield strength, $R_{p0.2}$, that depends

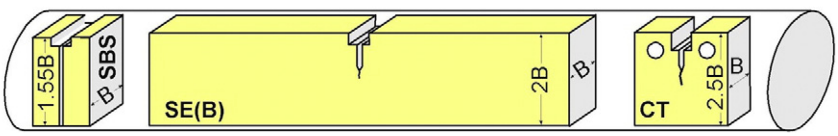

Fig. 1. Restricted specimens configuration to adjust the tendon rod diameter: a) bend specimen – SE(B); b) short bar specimen – SBS; c) compact specimen – CT.