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Environment-assisted failure of structural tendons for construction and building applications

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HIGHLIGHTS

- Upper bounds of induced damage in tendon bars derived from fracture toughness.
- Prevention of seawater-induced damage from stress intensity factor threshold.
- Bars safe-life guaranteed by proof loading rather than non-destructive testing.

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ABSTRACT

The work focuses on the environment-assisted crack growth conditions and addresses the threshold stress intensity factors of three commercial high-strength steel bars widely used in construction and building tensile applications. To quantify the sensibility to stress corrosion cracking, chevron-notched short bar specimens were simultaneously subjected to tension tests and hydrogen embrittlement in both artificial seawater and ammonium thiocyanate solution. The latter was used to enhance the stress corrosion damage and to reveal the fracture morphologies that characterize the rupture of the bars. Thus, new insights regarding the lifetime of the bars in seawater environment are brought into attention.

1. Introduction

The use of high-strength steel bars in structural applications for geotechnical engineering, bridge and building construction or rehabilitation has increased significantly in the last two decades. During this period various failure cases have been reported, and these include stress corrosion failures due to hydrogen embrittlement [1].

In 2012, and after 10 years of performance, 3 broken bars (7.5 m length and 36 mm diameter) from 340 prestressed anchors used to sew a vault dam crack in Spain [2], were detected in a routine inspection. Rupture analysis and hydrogen embrittlement tests of cylindrical circumferential-notched specimens [2] made from the broken bars showed that the fractures were triggered by small cracks that started at the bar surface.

Hydrogen embrittlement was also deemed as the main cause of the failure of five bolts in 2014 in the Leadenhall Building (otherwise known as the Cheesegrater), the fourth tallest building in the City of London [3]. Consequently, dozens of bolts ranging from 200 mm to 1200 mm long, with diameters of between 50 mm and 75 mm were replaced and secured in-place [3].

In 2014, high concentrations of hydrogen and the presence of large-size inclusions at microstructure level, in 2 of the 98 bars, (of 10 m length and 40 mm diameter) generated an early degradation of the foundations of a wind turbine located in China [4].

Before the San Francisco Bay Bridge was opened to traffic in 2013, the constructors had to face and solve some problems due to the inadequacy of its steel-bar specifications regarding environment-assisted cracking, which still raises questions about reliability [5,6]. In fact, site inspections performed in June 2015 revealed tiny cracks in some of the bars on the new bridge tower which potentially endangered the more than 400 remaining fasteners (of 40 mm diameter) used to secure the tower to the foundations, as seismic stabilisers [7].

From the aforementioned cases, it is clear that the environment-assisted failure occurs in tensile high-strength steel bars, but this is not explicitly recognized in the current dedicated

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codes [1]. The standards typify the structural designation of bars by resistance criteria [8–10] and do not consider damage tolerance. Thus, present commercial bars differ significantly in manufacturing and chemical composition requirements [11,12]. Microalloying and/or thermomechanical treatments applied after hot rolling assure high-strength, given that the microstructure is fully pearlitic or ferritic-martensitic, of a random orientation that does not propitiate directional cracking.

Today, Fracture Mechanics is a powerful tool in failure analysis [13], with existing knowledge in this field being applied in structural design; a current route that can be followed by designers to prevent fatigue or brittle fracture of steel structures is given in Eurocode 3 [14]. According to this methodology, a pre-existing damage of a conservative and empiric fundament is postulated in order to limit the design load on the basis of the damage tolerance of the designated material. In this view, this research does not address the initiation of environmental damage and focuses on the environment-assisted crack growth conditions, and in particular on the threshold stress intensity factors of three commercial high-strength steel bars intensively used for construction and building tensile applications.

In order to experimentally quantify the sensibility to stress corrosion cracking, fatigue pre-cracked chevron-notched short bar specimens (SBS) [15] were simultaneously subjected to tension and hydrogen embrittlement tests in artificial seawater. Additionally, the aqueous solution of 20% ammonium thiocyanate – FIP [16] medium, was employed to enhance the intensity of damage and to reveal the fracture morphologies that characterise the ruptures of the bars. The toughness of each steel-bar class was also explored, as an upper bound of the environment-induced damage.

2. Material characteristics and testing design

The tested high-strength steels (hereinafter A, B and C steels), of martensite and eutectoid structure, are commercial hot rolled bars of cylindrical smooth, either in full or only end-threaded configurations, and various diameters. Their chemical compositions, given in Table 1, reflect the presence of microalloying elements such as Cr and Cu designated to increase the pitting corrosion resistance [8,17].

Fig. 1 shows the stress-strain characteristic curves of the steels, obtained by tensile testing cylindrical smooth specimens, of 5 mm diameter, according to ISO 15630-3 [16] with their mechanical properties being summarized in Table 2. These agree with the results of the full-size testing in tension of bars provided by the manufacturers. The absence of the localised transition from elastic to plastic behaviour in steel B, as well as the reduction in area, indicates higher thermo-mechanical straining processing when compared with the steel C.

Scanning electron microscopy (SEM) images that show the microstructure features of each tested steels are presented in Fig. 2. These were obtained from standard metallographic specimens, 4% Picral etched. Fig. 2a reveals the clusters of typical coarse laths of martensite and small black angular patches of retained austenite and discrete carbides particles resulted by quenching and tempering the steel A, [18,19]. The fully eutectoid steels B and C are illustrated in Fig. 2b and c, from which the significant differences in interlamellar spacing and sizes of pearlite colonies are visible. In steel C, the microalloying elements (Cr, Ni, and Cu) concentrated at the ferrite-cementite interface, and the presumably low level of thermo-mechanical straining, justify the presence of such coarse pearlite when compared with that found in the B steel [20].

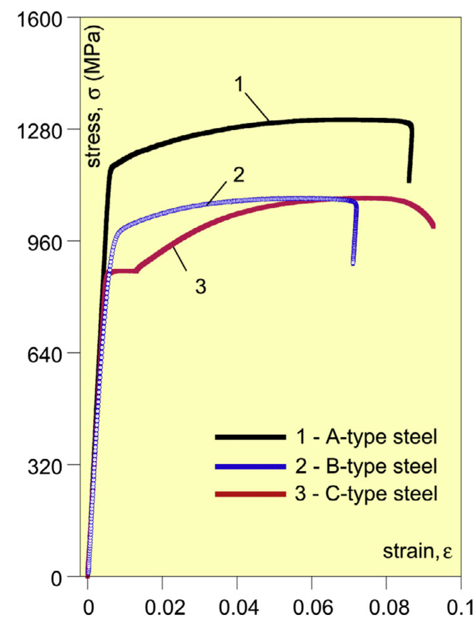

Fig. 1. Stress-strain curves of tested steels.

The toughness of the bars was determined from sets of three fatigue-precracked chevron-notched short-bar specimens (SBS) [3], with a width of B = 17 mm, (Fig. 3a). The tests were performed on specimens that allowed the crack propagation in the direction perpendicular to the bar axis, according to the methodology given in the ASTM E1304 [15,11]. All of them were previously fatigue precracked by applying constant cyclic loads ranging from 0.5 kN to a maximum corresponding to a stress intensity factor about 30 $MPam^{1/2}$. In all cases, the average number of cycles applied to each specimen was about 16,000 at a frequency of 5 Hz. A crack mouth opening displacement (CMOD) extensometer was initially used to control the fatigue precracking, and then the crack extension during the fracture tests.

The same type of SBSs, precracked by fatigue, was employed in the stress corrosion (SC) tests performed according to [11] to characterise the environment-assisted crack growth conditions and determine the threshold stress intensity factors. The sensibility of the bars to cracking was studied at room temperature in artificial seawater (aqueous solution of 3.5% sodium chloride), though the aqueous solution of 20% ammonium thiocyanate was also used given that it enhances environmental damage and propitiates the detection of fracture mechanisms at micro scale. The SC tests were carried out according to the procedure presented in [11]. The experimental arrangement and the specimen configuration are depicted in Fig. 3. The fatigue pre-cracked ligament remains immersed into the aggressive medium throughout the test. Load is horizontally applied through an elastic loading train whose com-

Table 1
Chemical composition of the tested A, B and C steel bars (%weight).

Steel bar	C	Mn	Si	P	S	Cr	Ni	Cu	V	Mo	Fe
A	0.48	0.66	1.78	0.011	0.002	0.44	0.02	0.01	–	–	Bal.
B	0.68	0.61	0.25	0.010	0.010	0.03	0.025	–	–	–	Bal.
C	0.64	0.82	0.24	0.01	0.03	0.8	0.16	0.21	0.1	0.04	Bal.