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Failure analysis of cold drawn eutectoid steel wires for prestressed concrete

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Abstract

In this paper, a failure analysis of cold drawn eutectoid steel wires for prestressed concrete is presented. Results demonstrated that progressive cold drawing affects clearly the fracture performance of the materials, so that the most heavily drawn steels exhibit anisotropic fracture behaviour with crack deflection, i.e., a change in crack propagation direction which deviates from the original mode I propagation and approaches the wire axis or cold drawing direction, thereby producing a mixed mode stress state after a *pop-in* detectable in the load–displacement plot. An approximate procedure is proposed in the paper to estimate the fracture toughness of heavily drawn steels in both longitudinal (wire axis) and transverse (perpendicular) directions, on the basis of the critical load at the pop-in situation and at the critical failure instant (maximum load). In addition, a fracture criterion is proposed so that it can be used as a design criterion in real engineering situations involving prestressed concrete structures.

Keywords: Prestressing steel; Damage tolerance; Structural integrity; Fracture toughness; Directional toughness

1. Introduction

The study of high-strength prestressing steels is of special importance in civil engineering structures where prestressed concrete is widely used [1]. These steels are manufactured from a hot rolled bar which is heavily cold drawn in several passes to obtain the commercial prestressing steel wire with increased yield strength obtained by a strain-hardening mechanism. Thus, although it is clear that cold drawing improves the (traditional) mechanical properties of the steel (i.e., those properties useful for regular service), the

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strong plastic deformations in the wire axis (drawing direction) during manufacture may produce anisotropic fracture behaviour in air [2,3] and in aggressive environments [3–5].

This paper offers a fracture mechanics approach to the design of prestressed concrete structures. Assuming that a crack may always be present in the material due to previous manufacturing defects or the combined action of both the mechanical and the chemical environment, design on the basis of fracture mechanics principles is today a useful tool for modern civil engineers. With this in mind, fracture criteria are considered as design criteria to evaluate the damage tolerance capacity of prestressing steel wires with sharp surface defects in the form of cracks produced by any subcritical mechanism of cracking: mechanical fatigue, stress-corrosion cracking, hydrogen embrittlement or corrosion fatigue.

2. Experimental procedure

2.1. Materials used

A commercial prestressing steel wire was used in this work, together with the previous steps of the manufacture route, to have steel wires which have undergone progressive levels of plastic deformation during straining by cold drawing. Table 1 shows the chemical composition (common to all steels) and Table 2 gives the nomenclature and diameter of all the steel wires (the number of drawing steps applied to each one is indicated by the digit in its own name), as well as the mechanical properties of the steels with different degrees of cold drawing.

Fig. 1 shows a plot of the stress–strain curves of the steels (experimentally measured by means of standard tension tests), showing a clear improvement of *traditional* mechanical properties after the manufacturing process by cold drawing, i.e., both the yield strength and the ultimate tensile stress increase progressively as a consequence of the strain hardening mechanism. This guarantees that the engineering performance of the prestressing steels is adequate from the point of view of classical structural engineering, i.e., the yield strength of the resulting material is high enough to maintain its structural behaviour in the elastic regime.

In spite of this enhancement of mechanical properties, the effects of manufacturing are not well known from the point of view of modern fracture mechanics approaches and damage tolerance analyses to guarantee the structural integrity. Thus, this item requires further research to elucidate the consequences of

Table 1
Chemical composition (wt%) of the steels

C	Mn	Si	P	S	Cr	V	Al
0.80	0.69	0.23	0.012	0.009	0.265	0.060	0.004

Table 2
Diameter reduction and mechanical properties of the steels

Steel	0	1	2	3	4	5	6
D_i (mm)	12.00	10.80	9.75	8.90	8.15	7.50	7.00
D_i/D_0	1	0.90	0.81	0.74	0.68	0.62	0.58
σ_Y (GPa)	0.686	1.100	1.157	1.212	1.239	1.271	1.506
σ_R (GPa)	1.175	1.294	1.347	1.509	1.521	1.526	1.762
P (GPa)	1.98	2.26	2.33	2.49	2.50	2.74	2.34
n	5.89	8.61	8.70	8.45	8.69	7.98	11.49

E, Young's modulus; σ_Y, yield strength; σ_R, ultimate tensile stress (UTS) P; n, Ramberg-Osgood parameters: $\varepsilon = \sigma/E + (\sigma/P)^n$.