ANISOTROPIC FRACTURE BEHAVIOUR OF PRESTRESSING STEELS

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ABSTRACT

Cold-drawn prestressing steel wires show an anisotropic behaviour in fracture tests because of their highly oriented microstructure. This behaviour, observed from a phenomenological point of view, is studied in this paper by using Fracture Mechanics concepts. An experimental program which includes testing of steel in isotropic and anisotropic form, before and after cold-drawn processing respectively, has been undertaken. The energy release rate concept is applied in a bending test under mixed mode to determine the fracture toughness angular distribution in both materials.

INTRODUCTION

Cold drawn steel wires show a marked degree of fracture anisotropy (1), which results from the fabrication process. It is much easier to propagate cracks in the longitudinal rather than the transverse direction. This behaviour favours stress release at the tip of small cracks to the extent of stopping incipient stress corrosion cracks, as reported elsewhere (2).

Fracture mechanics concepts begin to be used for predicting life of stressed steel wires, particularly when subjected to fatigue (1,3). All such treatments consider isotropic behaviour. The purpose of this paper is to explore the degree of anisotropy of cold drawn wires used for prestressing concrete and to check the suitability of the available fracture criteria for estimating the critical load of such components.

THEORETICAL CONSIDERATIONS

There are two sources of anisotropic fracture behaviour. If the material is elastically anisotropic the angular distribution of stresses near the crack depends on material properties and hence on the position of the material axes with respect to the crack; as a consequence elastic anisotropy is the different fracture resistance which the material may exhibit for each crack propagation direction. In both cases fracture can occur at unexpected loads and propagate along unexpected directions. Therefore, in order to evaluate the anisotropy effects on fracture, it seems adequate to ascertain its origin.

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For prestressing cold drawn steel wires, elastic anisotropy, if it exists, must be transversal isotropy in normal planes to the wires axis, because of the manufacturing process. However, measurements carried out by the authors provide the same values for elastic constants in the transversal and longitudinal directions. The propagation velocities of elastic waves, which are determined by Young's modulus, are equal in both directions, and the shear transversal modulus, obtained from torsion tests, agrees with the theoretical value for an isotropic material, derived from longitudinal Young's modulus and Poisson's ratio. These data indicate that the steel is elastically isotropic and therefore, its anomalous behaviour is originated by an anisotropic fracture resistance. Another reason which supports this idea is based on the significant changes which the material shows in its anomalous behaviour as temperature decreases. It is a well known fact that elastic constants are only lightly influenced by temperature while fracture resistance is largely influenced.

To consider the different crack propagation resistance along each direction, a maximum energy release rate criterion, as a natural generalization of the Griffith rupture theory, will be used. It states that fracture occurs by propagation of the crack along the direction for which a physical quantity, the energy release rate G, is maximum and reachs a critical value which is a material constant G_c. i.e.:

$$\text{Max } G(\theta) = G_c \tag{1}$$

where θ is the polar angle (Fig. 2).

If G_c depends on the direction, equation (1) may be modified in the form:

$$\text{Min } \{G_c(\theta) - G(\theta)\} = 0 \tag{2}$$

According to equation 1, for isotropic materials the direction θ_c along which crack propagation will start, can be predicted without knowing the critical value G, because such direction is that for which G is maximum. However, to predict the critical loads which cause fracture, the value G_c needs to be known.

For anisotropic fracture resistance materials, the curve $G_c(\theta)$ is required for both predictions. If the crack plane is a physical plane of the material, it is an intrinsic curve and can be obtained experimentally from a particular type of test. The test design must permit to apply different mixed load modes so that the angle θ_c corresponding to the direction of crack propagation changes from one test to another. Thus, by recording the load at the start of crack propagation, the value $G_c(\theta_c)$ is calculated in each test and the curve $G_c(\theta)$ is obtained from the data of various tests.

In this work antiplane load mode is not considered and the mixed load mode is varied by changing the ratio K_{II}/K_I of the stress intensity factors corresponding to the plane modes. An expression for $G(\theta)$ in plane strain which can be found in references (4, 5) is:

$$G(\theta) = \frac{1 - \nu^2}{E} K_I^2 \left(f_1(\theta) - f_2(\theta)\, k + f_3(\theta)\, k^2\right) \tag{3}$$

where E, ν are Young's modulus and Poisson's ratio, respectively, $k = K_{II}/K_I$ is the stress intensity factors ratio and $f_i(\theta)$ are non-dimensional functions defined in Fig. 1.

For values of θ, $\frac{-\pi}{2} < \theta < 0$, $G(\theta)$ can be determined by taking into

account that

$$G(-\theta,k) = G(\theta,-k) \tag{4}$$

The theoretical direction of crack propagation for an isotropic material is given in Fig. 2. The curve has been found by determining for each ratio K_{II}/K_I the angle θ_c that maximizes G, according to equation 3. These results will be used to show the anisotropic behaviour by comparing theoretical predictions (assumming isotropy) with experimental data. Also, as a consequence of the anisotropic behaviour G_c must not be a constant.

TEST DESIGN AND ANALYSIS

The test to be designed has to fulfill some conditions. The first and the most important one consists in being able to combine modes I and II in variable proportions which should be adjusted before the test. This K_{II}/K_I ratio has to be independent of the specimen geometry since the decision about its numerical value has to be taken as a function of previous results. Another important aspect of this test comes from the fact that the specimens have to be cut from wires whose diameter can be as small as 7 mm. Then the specimens can have small transverse dimensions and unlimited geometry. This condition greatly simplifies the work since many of the standard requirements can be used (tolerances, fatigue, cracking, etc.).

All the conditions which have been described drive us to the conclusion that a bending test is the only possibility. At the beginning, a 3 or 4 point symmetric bending specimen with a slant crack was considered but it was rejected because of practical reasons. Finally 3 and 4 point unsymmetric bending specimens were adopted (Fig. 3). As the loading points are usually far from the top of the crack it is possible to design the optimal dimensions of the specimen by supposing that K_I factor is proportional to the bending moment and K_{II} factor is proportional to the shear force at the crack cross section.

Is the case of the 3 point bending test, three parameters were considered to obtain an optimal (maximum) K_{II}/K_I ratio. These parameters were a/w, c/L and L/w. This research was made simultaneously by way of the simple bending-moment and shear force calculation and by way of a finite element analysis. The results can be summarized by saying that the crack depth and the load position, a/w and c/L, have only a little influence on the K_{II}/K_I ratio.

The aspect ratio of the specimen, L/w, has a higher influence: the smallest value of L/w corresponds to the highest value of K_{II}/K_I. Nevertheless, if we take into account that the specimen width, W, can be as small as 6 mm., it was decided to adopt a non optimal value of L/w, namely 4, because of practical reasons. In this way the specimen would be the same as in BS5400 except for the position of the load which is located at c/L = 0.25. With these dimensions the maximum value of K_{II}/K_I which was expected was 0.1. To get higher values a new test has to be designed.

This new test is also a bending test in which bending moments at the crack cross section are reduced to a minimum. This can be achieved with a 4-point bending specimen (Fig. 3). In this specimen c should be equal to L/4 to get a pure mode II. Nevertheless, a small error in the position of the crack implies a very important mode I contribution. In any case, if we take into account the experimental precision with which the distance c can be measured, it is possible to obtain K_{II}/K_I values larger than unity.

The computation of K_I and K_{II} factors in a mixed mode problem can be really involved. Some methods can be found in the literature for mixed mode separation (6,7). In this case the associated displacement fields method (8) has been used combined with a finite element discretization and analysis of the specimens. As the specimens which have been chosen are geometrically symmetric, this method reduces to the analysis of a symmetrical and an anti-symmetrical problem and to the computation of the corresponding J_I and J_{II} integrals. The finite element mesh consists of 307 nodes and 94 elements to discretize half of the specimen since both loading cases can be reproduced by the adequate boundary conditions. The elements are 8 node quadratic isoparametric quadrilaterals and 6 node triangular elements (9). J_I and J_{II} integrals reduce to J integral in each of the loading cases. Then a standard subroutine was used to compute the path integral along 4 integration paths. The mean value among these 4 results was chosen to be the most representative value. As the analysis was made in a plane stress situation, K_I and K_{II} were compute as

$$K_I = \sqrt{E\, J_I} \quad (5)$$

$$K_{II} = \sqrt{E\, J_{II}} \quad (6)$$

Numerical results corresponding to both specimens are shown on Fig. 3. These results can be plotted as a function of bending moment and shear force at the crack cross section to get a reasonably narrow band which permits to estimate K_I and K_{II} factors in other loading conditions. Good results are obtained by means of this approach as long as load application points are moderately far from the crack cross section.

EXPERIMENTAL RESULTS

Two eutectoid steels have been used in this work: a commercial 7 mm. diameter cold drawn prestressing wire and the 12 mm. parent hot rolled, patented bar. Both steels have the same chemical composition, which is shown in table I.

TABLE I.- Chemical Composition

C%	Mn%	Si%	P%	S%	Cr%	Ni%	Cu%
0.78	0.67	0.21	0.012	0.022	0.03	0.02	0.02

After rolling, the 12 mm. diameter bar is patented by cooling from the austenitic condition in a molten lead bath to produce fine pearlite. The wire is obtained by cold drawing this bar in six passes, to achieve an overall reduction of 66%, and finally a stress-relieving process is applied involving exposure at about 400°C for a few seconds. Mechanical properties of both materials are presented in Table II. The K_{IC} -values included are values estimated from fracture tension tests on fatigue surface cracked cylindrical specimens, by using the K_I- expressions presented in (1). They are not valid K_{IC} values in the ASTM E-399 sense, but the value of the stress intensity factor at fracture which does not depend on crack size.

TABLE II.- Mechanical Properties

	E (MPa)	0.2% PS (MPa)	UTS (MPa)	Elongation (%)	RA (%)	K_{IC} (MPa $m^{1/2}$)
12 mm. bar	186000	760	1260	8.5	26	60
7 mm. wire	184000	1560	1800	6.5	35	100

Identical bending specimens have been machined from both materials to avoid possible size effects. The specimens were rectangular beams 6 mm. wide and 3 mm. thick. The longitudinal axis of these specimens was the original axis of the cylindrical samples. The fatigue cracks were nominally normal to the longitudinal direction and with a depth of about 0.5 times the width of the beam. The wires and bars were fatigue cracked in tension, before machining the bend specimens, from a surface notch of straight front which was taken as the thickness direction to machine the beam. In this way the fatigue cracking process can be better controled and the front of the resulting crack is practically straight and parallel to the thickness direction.

The tests have been carried out by controlling displacement and in the case of four point bending test a three pointed rigid beam was used, in order to transform the load caused by the crosshead into two proportional loads applied on the specimen at the selected positions. During the test the load was continously recorded and the fatigue crack observed by means of a magnification 20X microscope attached to the testing machine, in order to detect the exact time of unstable crack growth. After fracture the angle of crack propagation θ_c and the dimensions of the initial crack were measured on the broken specimens. From these data and the fracture load, the values K_I, K_{II}, $G(\theta_c)$ at fracture were calculated and plotted on figures 2 and 4.

DISCUSSION OF RESULTS AND CONCLUSIONS

To study the anisotropic fracture behaviour of cold-drawn prestressing steel we will try to extend the validity of fracture criteria which have been considered to analyze mixed mode fracture in isotropic materials. For this purpose, the original steel bars from which prestressing steel wires are drawn have been included in the testing program along with the anisotropic prestressing steel wires.

Experimental crack propagation directions corresponding to isotropic steel bars have been compared with theoretical predictions according to the fracture criterion which has been previously detailed (Fig. 2). Coincidence is perfect for all the experimental data which are availible up to now. Moreover these results clearly show that the fracture energy release rate, $G_c(\theta_c)$, is independent of the crack propagation direction and of the type of test (3 or 4 point bending). Its value is coincident with the corresponding fracture toughness estimate (Table II) and seems to be a material constant. Then generalized Griffith fracture criterion has been checked to be a valid criterion to describe the fracture behaviour of steel bars. It will then be used to evaluate the anisotropic effects which have been produced by the cold drawing process.

This effect is shown on Fig. 4. In the longitudinal direction the fracture toughness reduction is 75% of the original value while in the transverse direction the increment of fracture toughness can be estimated as 50% of the original value if one refers to the data which have been displayed on Table II. The reason for not presenting transverse direction values is that it is extremely difficult to drive the crack into this direction with the present testing conditions. The reason for this behaviour is based on the extremely anisotropic fracture resistance which has been found on this material. These results were expected from a qualitative point of view but present results show the quantitative importance of the anisotropic behaviour which is being studied.

Three conclusions can be drawn from this work: The anisotropic fracture resistance has been confirmed and a procedure has been proposed to check and to analyze this effect. The fracture criterion which has been used is an extension of an isotropic materials criterion and permits to predict the critical load.

These techniques are suited for estimating the advantages and drawbacks of wire anisotropy. No doubt, they should be introduced in analyzing fatigue and stress corrosion, although their implementation proves to be difficult.

SYMBOLS

G = Energy release rate
θ = Angle
ν = Poisson's ratio
E = Young's modulus
K_I/K_{II} = Stress intensity factor
$f_i(\theta)$ = Non-dimensional functions
$k = K_{II}/K_I$ = Stress intensity factor ratio
J_I, J_{II} = Integral expressions
The subscript c means critical value.

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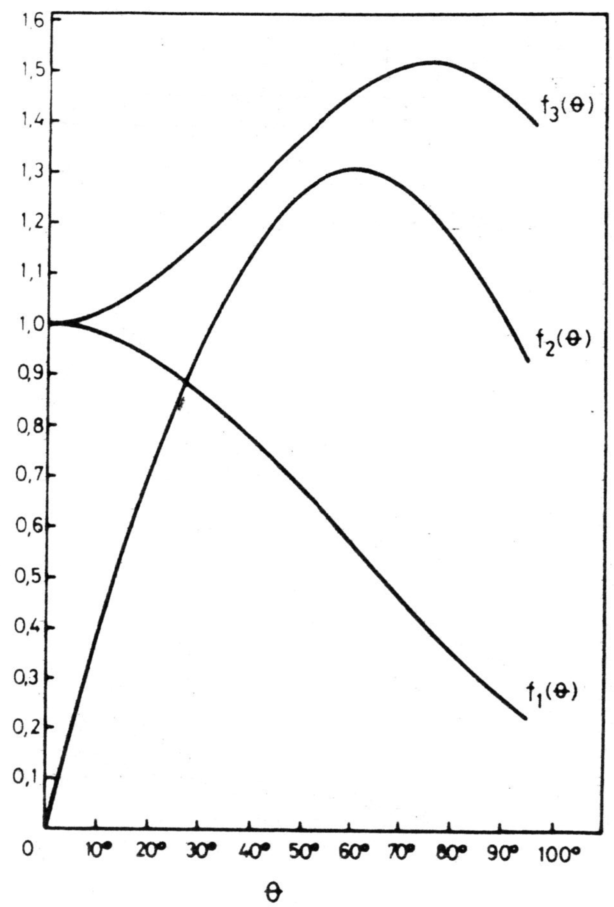

Fig. 1.- Dimensionaless functions to define G(θ).

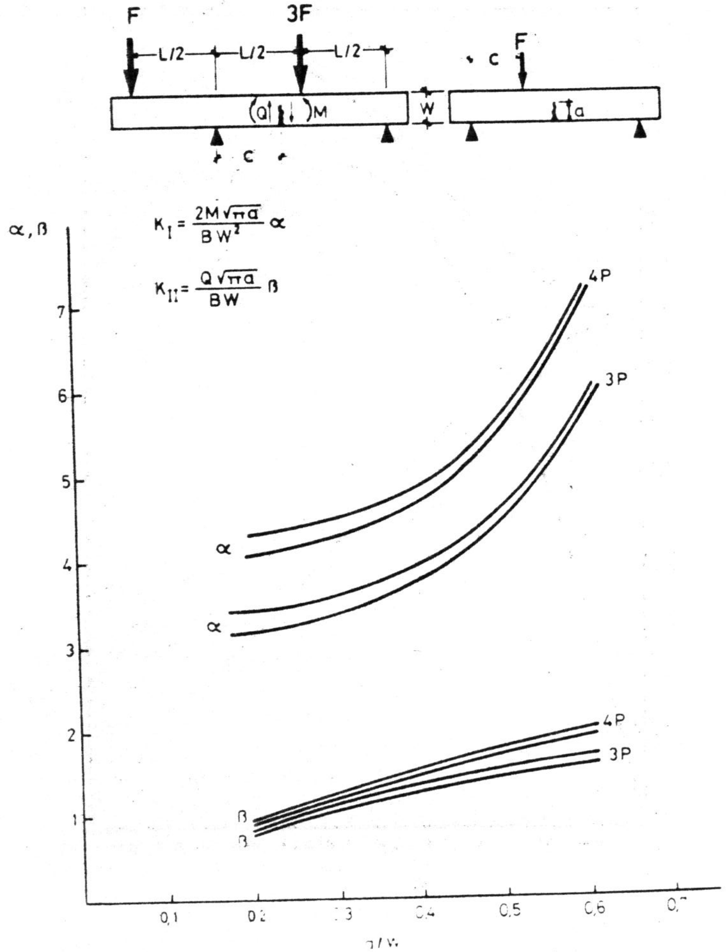

Fig. 3.- Numerical results for stress intensity factors in 3P and 4P bending tests.

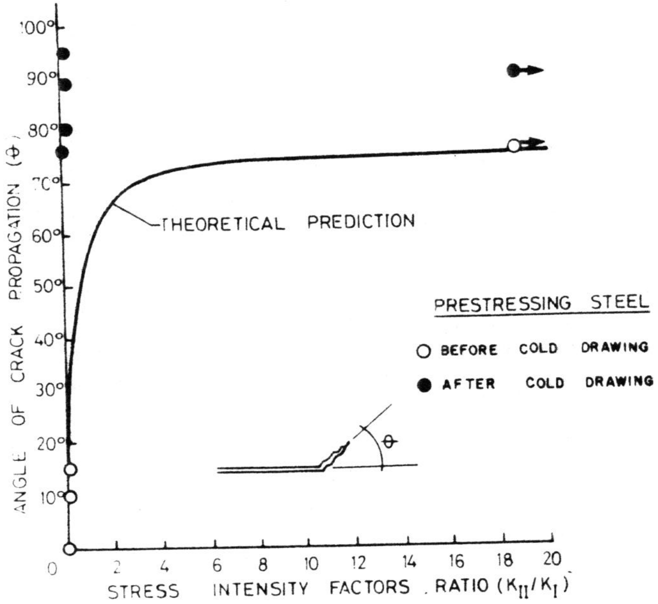

Fig. 2 .- Crack propagation direction for mixed load modes.

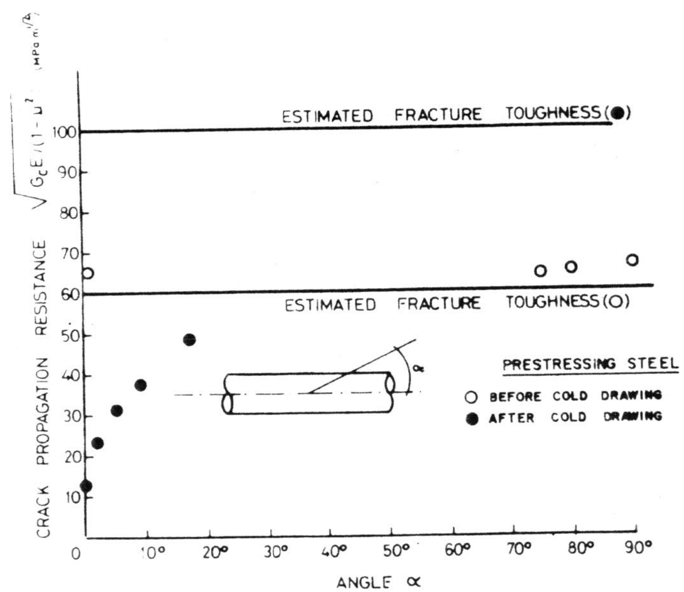

Fig. 4.- Fracture resistance for different crack propagation directions.