ON FATIGUE CRACKING IN PRESTRESSING STEEL WIRES

A. Valiente, V. Sánchez-Gálvez and M. Elices

Escuela T.S. de Ingenieros de Caminos, Canales y Puertos Universidad Politécnica de Madrid,
Ciudad Universitaria s/n, Madrid-3, Spain

ABSTRACT

Fatigue of prestressing steel is studied according to fracture mechanics principles. Initiation and propagation crack aspects are considered separately and analysed experimentally. From the data obtained a theory is put forward which predicts fatigue life of prestressing steel wires. Predictions are compared with experimental results. Residual stresses in the wires are also considered.

KEY WORDS

Fatigue; prestressing steel wires; crack initiation; crack propagation.

INTRODUCTION

Eutectoid cold drawn steels wires are mainly used in prestressed concrete. The importance of such material may be reckoned by its world production, over 10^6 tons. per year. Prestressed concrete is progressively more used for building structures, which must withstand dynamic loads, such as earthquakes in nuclear power plants, traffic loads in highway or railroad bridges, waves in off-shore structures, etc.. In such applications, the fatigue behaviour of prestressed concrete has to be included in a suitable design of the structure.

Despite the importance of the problem, the fatigue behaviour of prestressing steel has been given very little attention in the past. The reason is the general assumption that the stress ranges in the prestressing steel usually fall below the values regarded as significant for fatigue (Price, Tricklebank and Hambly, 1982; Taylor and Sharp, 1978). Therefore most of the research effort in the last decades has been centered on the fatigue behaviour of plain concrete and reinforcing bars, and very little information is available about the fatigue behaviour of prestressing steels.

Nevertheless this assumption may be unsafe if an overload causes cracking of the concrete. When such cracks are not completely closed by the prestressing force, they magnify locally the stress oscillations in the prestressing steel due to dynamic loads. Due to these oscillations a fatigue crack may be initiated and grow in the steel wires. Thus the axial fatigue behaviour of prestressing steel is a very important parameter for the dynamic design of prestressed concrete structures.

On the other hand, in accordance with most prevailing Standards, the scarce published data of prestressing steel fatigue do not adequately distinguish between crack initiation and crack propagation. Recent requirements, in particular the Model-Code (CEB-FIP, 1978) issued by the CEB (Comité Euro-International du Béton), still specifies for this material an endurance limit from classical Wohler-type or S-N curves.

Recently, the authors have published the first experimental results of fatigue crack growth in prestressing steel wires (Sánchez-Gálvez, Elices and Valiente, 1982). The aim of this paper is to complement such research by studying fatigue crack initiation in prestressing steel wires. From these data a calculation method is developed which allows the prediction of the fatigue life of a prestressing steel wire.

THEORY

The number of cycles at fracture N_f of a wire loaded cyclically in tension at a constant stress range is considered as the sum of two terms

$$N_f = N_i + N_p \qquad (1)$$

where N_i is the number of cycles for crack initiation, and N_p is the number of cycles for crack propagation, i.e. for crack growth from initial crack a_o, after initiation up to the critical crack depth a_c, at which failure occurs.

It will be assumed that the crack propagation law is the same for the whole range of ΔK and a values, provided $\Delta K > \Delta K_{th}$:

$$\frac{da}{dN} = C\ (\Delta K)^n \qquad (2)$$

where the values of the constants C and n for prestressing wires were measured previously (Sánchez-Gálvez, Elices and Valiente, 1982) and are 11×10^{-12} and 2.3 respectively if MPa $m^{1/2}$ and m/cycle units are used.

Propagation life N_p can be calculated by integrating equation (2) if expressions of K_I for cracked wires are available. Integration limits will be the critical crack size a_c which causes fracture for the maximum load applied and the size a_o of the crack at the end of initiation process. This will be defined below in a conventional manner from the physical condition which is assumed for crack initiation.

For crack initiation, it will be assumed that a cyclic plastic strain must appear at least in a region of about 100 µm, i.e. a crack will not be created unless a plastic zone about 100 µm. of size exists under cyclic loading. This assumption has been introduced previously by other authors (Forsyth, 1971), by assuming that the subcritical crack growth, i.e. for crack depths below about 100 µm., is controlled by the plastic strain range applied to the specimen. According to this condition an initial effective crack inmediately after initiation is considered which extends to the zone where cyclic plastic strain has occurred.

Provided that the necessary plastically strained zone exists, the number of cycles to initiate a crack will be supposed to be a function of the stress intensity range ΔK_o corresponding to the initial effective crack.

$$N_i = f\ (\Delta K_o) \qquad (3)$$

More precisely a power-law formulation will be employed

$$N_i = C'\ (\Delta K_o)^{n'} \qquad (4)$$

as was used previously by other authors for other materials (Barnby and Holder, 1976; Jack and Price, 1970; Salah el din and Lovegrove, 1982). As indicated eq. (2) may be used to determine N_p and eq. (4) provides N_i, so that the number of cycles at fracture N_f can be obtained.

Three types of specimens are used in this research: plate samples, single notched, machined from prestressing steel wires, for which K_I formulae are available (Rooke and Cartwright, 1976), plain specimens, in the as-delivered condition, and precracked specimens for which expressions of K_I have been recently proposed (Elices, 1983; Valiente, 1980).

For plate samples both the Creager-Paris (1967) and Neuber stress distributions (Peterson, 1974) ahead of the notch will be used to ascertain the plastic zone size:

$$\sigma = \frac{K_I}{\sqrt{2\pi}}\ (r - \frac{\rho}{2})^{-1/2} + \frac{K_I}{\sqrt{2\pi}}\ (r - \frac{\rho}{2})^{-1/2}\ \frac{\rho}{2}\ (r - \frac{\rho}{2})^{-1} \qquad (5)$$

$$\sigma = \sigma_{max}\ \frac{\rho}{2}\ (r - \frac{\rho}{2})^{-1} \qquad (6)$$

where r is the distance from the notch root and ρ the root radius.

The plastic zone size r_y is assumed to be the depth for which σ equals the yield cyclic stress σ_y. Finally the stress intensity range ΔK_o is calculated from the initial crack depth a_o equal to the notch depth plus the plastic zone size r_y.

For precracked wires, the following expression obtained from a finite element calculation gives K_I as a mean value along the crack front (Valiente, 1980).

$$K_I = \sigma\sqrt{\pi a}\ \{0.473 - 3.286\ (\frac{a}{D}) + 14.797\ (\frac{a}{D})^2\}^{1/2}\ \{(\frac{a}{D}) - (\frac{a}{D})^2\}^{-1/4} \qquad (7)$$

where a is the crack depth, D the diameter of the wire and σ the remote applied stress. This expression is only valid if $\frac{a}{D} > 0.15$. For values of a/D less than 0.15, K_I has been calculated numerically (Elices, 1983) and is expressed as:

$$K_I = M\ \sigma\sqrt{\pi a} \qquad (8)$$

where M is a non dimensional correction factor which varies along crack front, but independent of a/D if a/D < 0.15. Then, its mean value 0.94, has been considered in order to have a full range of K_I:

$$K_I = 0.94\ \sigma\sqrt{\pi a} \quad \text{for} \quad \frac{a}{D} < 0.15 \qquad (9)$$

The stress intensity factor of eq. (7) has shown to be a good fracture parameter for prestressing steel wires, since its value at fracture is quite independent of crack size. Therefore eq (7) can be used to determine the critical crack size a_c, by equating its right hand side to the value at fracture of K_I, K_c, previously obtained.

For plain samples, the necessary condition of plastic straining may be achieved even with a nominal applied stress below the yield cyclic stress, because tensile residual stresses are present at the surface, as has been measured recently by the authors (Elices, Maeder and Sánchez-Gálvez, 1983). Tensile residual stresses as high as 200 MPa may be found extending up to about 250 μm. depth. In such a case the nominal stress plus the residual stress may cause plastic straining at the surface, the plastic zone size being about 250 μm. i.e. the order of magnitude required for crack initiation.

EXPERIMENTS.

The material used is a commercial 7 mm. diameter cold drawn steel wire in the stress-relieved state conforming to Euronorm 138. (ECSC, 1979). Its chemical composition and mechanical properties are shown in Table 1.

TABLE 1. Composition and Mechanical Properties of Steel Tested

C %	Mn %	Si %	S %	P %	UTS MPa	0.2%PS MPa	El %	RA %	K_c MPa $m^{1/2}$
.78	.67	.21	.012	.022	1620	1400	6.5	40	108

The steel was patented by cooling from the austenitic condition in a molten lead bath to produce fine pearlite, after which it was cold drawn in six passes to achieve an overall reduction of about 66%. The drawn wires were stress-relieved by normal practice involving exposure at about 400°C for a few seconds.

Three types of specimen were employed in this research: plain specimens which had their surfaces degreased; notched specimens which were machined from a wire to a plate shape 2 mm. thick with a single U-shaped notch of different root radii, and pre-cracked specimens in which a starter notch, about 1 mm. deep was introduced with a jewellers saw and the fatigue pre-crack extended to produce a flaw of about 1.5 mm. total depth.

Plain specimens have been used to determine the cyclic stress-strain curve. In these tests a controlled strain wave is applied and the corresponding stress wave recorded until it becomes constant. Then the mean value of the strain wave is increased and a new stress wave obtained, etc. The number of strain oscilations to achieve a constant stress wave has been ten. Plain specimens have also been used in axial fatigue tests at constant stress range to measure the number of cycles at fracture, for different stress ranges and stress ratio less than 0.1.

Plate single notched samples have been used to obtain crack initiation data. Tests on these specimens consist of cyclic loading in tension at constant nominal stress range, low frequency and stress ratio less than 0.1. The number of cycles at crack initiation was determined directly by observing the polished surface of the specimen at notch root. A magnification 20X microscope was used for this purpose.

Finally, precracked samples have been used to measure the crack growth rate, in axial fatigue. The compliance method was used to obtain a continuous record of the crack depth during the test.

All tests have been performed in air at 20 ±1°C of temperature and a relative humidity of 50±5%. Different wave forms and stress ratio ranging from 0.1 to 0.9 have been used.

RESULTS AND DISCUSSION

Figure 1 shows the cyclic stress-strain curve as well as the monotonic stress -strain curve. As it can be seen, for stresses over 800 MPa aproximately cyclic plastic strains are produced, although the material would be elastic in a static test.

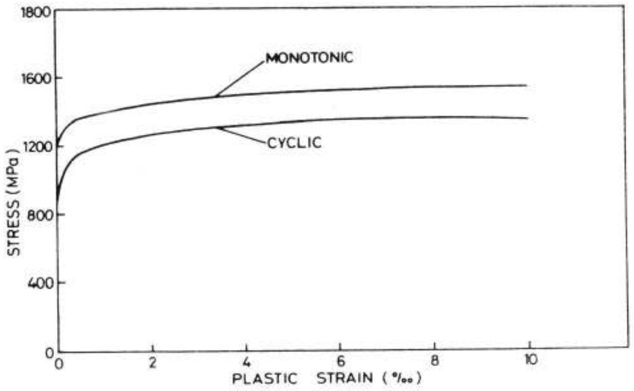

Fig. 1. Monotonic and cyclic stress-strain curves for prestressing steel.

Figure 2 shows the S-N results for fracture of plain samples in which an experimental fatigue limit of about 600 MPa is observed. This value agrees with the minimum applied stress range which must be added to a residual stress of about 200 MPa to achieve the necessary stress (800 MPa) to produce a cyclic plastic zone (see Fig. 1) and cause crack initiation. Therefore, the fatigue limit is determined by the crack initiation requirement provided that the stress intensity range, inmediately after crack initiation, is higher than the threshold ΔK_{th}.

Figure 3 shows the experimental results Log N_i vs. log ΔK_o for notched specimens with different root radius. As it can be seen all the results fit quite well with a straight line, showing the suitability of eq. (4). Then it is obtained

$$N_i = 5.88\cdot 10^6\ (\Delta K_o)^{-3.1} \qquad (10)$$

where ΔK_o has to be expressed in MPa $m^{1/2}$

Figure 4 shows the experimental results of fatigue crack growth rate vs. stress intensity range. As it can be seen eq.(2) agrees fairly well with the empirical results. Moreover no stress intensity range threshold is observed above 8 MPa $m^{1/2}$.

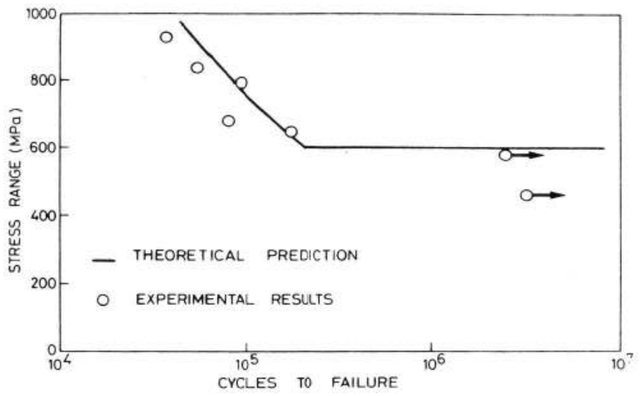

Fig. 2. Experimental and predicted S-N curves for prestressing steel.

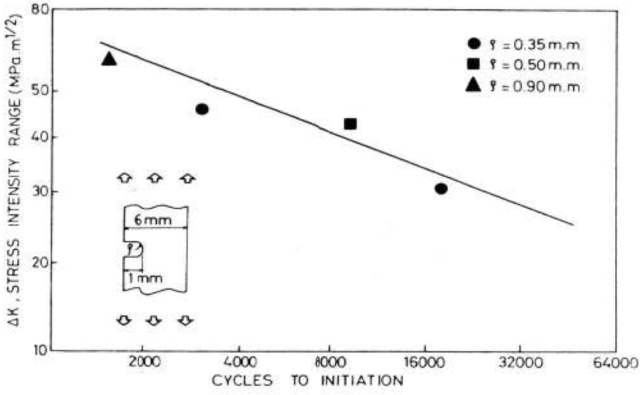

Fig. 3. Crack initiation data for prestressing steel.

Equation (10) can be used now together with the K_I expression of eq. (9) to predict the number of cycles for crack initiation in plain specimens. According to the assumptions an initial crack size of 250 μm. has to be used. For this crack depth the stress intensity range at fatigue limit may be calculated by using eq. (9) and a value of 16 MPa $m^{1/2}$, higher than ΔK_{th}, is obtained. Thus, it is confirmed that the crack initiation requirement is the critical condition which determines the fatigue limit. Adding the number of cycles for crack propagation obtained by integration of eq. (2) from eqs.(7) and (9), the number of cycles at fracture can be determined. Figure 2 illustrates the curve obtained, for a stress ratio of 0.1, along with the experimental results, and shows a good agreement between experiments and theory.

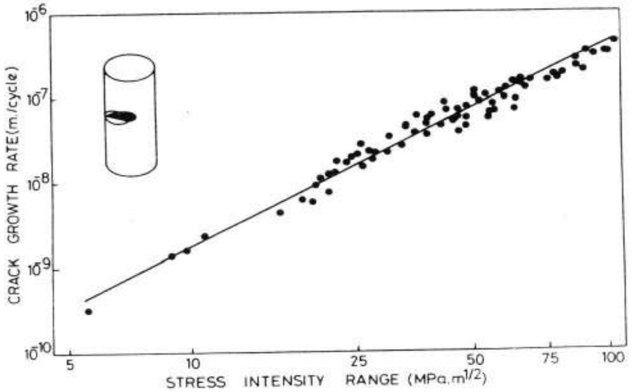

Fig. 4. Crack propagation data for prestressing steel.

CONCLUSIONS

At the first time fatigue of prestressing steel wires is studied on the basis of fracture mechanics concepts. Experimental results of crack initiation and crack propagation in these steels are provided.

From these data a theory is presented which predicts the fatigue life of a plain or flawed prestressing wire in tension. Thus, experimental S-N curves used in classical analysis of fatigue can be predicted from experimental data obtained in very little time. The curve corresponding to a stress ratio of 0.1 has been theoretically determined for a prestressing steel and compares well with experimental results. The observed deviations can be due to the intrinsic scatter of this type of test.

Finally, it must be pointed out the important effect that residual stresses cause, in crack initiation, according to the theory. Initiation life depends on the depth of the zone affected by residual stresses and classical fatigue limit depends on the magnitude of these stresses.

REFERENCES

Barnby, J.T., and R. Holder (1976). Int. J. Fracture, 12,631-637
CEB-FIP (1978). Model Code for Concrete Structures. Bulletin d'information n°124/125F (Paris).
Creager, M., and P.C. Paris (1967). Int. J. Fract. Mech., 3, 247-252
ECSC (1979). Prestressing Steels. Euronorm 138-79
Elices, M., G. Maeder and V. Sánchez-Gálvez (1983). Br.Corros. J., 18,80-81
Elices, M., (1983). Fracture of Steels for Reinforcing and Prestressing Concrete. In G.C. Sih (Ed). Fracture of Concrete and Reinforced Concrete, Martinus Nijhoff Publishers (to appear).
Forsyth, P.J.E. (1971). Proceedings Symposium on Crack Propagation, 76- Cranfield, U.K.
Jack, A.P., and A.T. Price (1970). Int. J. Fract. Mech., 6, 401-409

Peterson, R.E. (1974). *Stress Concentration Factors*. John Wiley and Sons, New York.

Price, W.I.J., A.H. Tricklebank, and E.C. Hambly (1982). *Proceedings IABSE Colloquium*, 487-494. Lausanne.

Rooke, D.P. and D.J. Cartwright (1976). *Compendium of Stress Intensity Factors*. Her Majesty's Stationary Office, London.

Salah el din, A.S., and J.M. Lovegrove (1982). *Proceedings IABSE Colloquium*, 247-254, Lausanne.

Sánchez-Gálvez, V., M. Elices and A. Valiente (1982). *Proceedings IABSE Colloquium*, 639-646, Lausanne.

Taylor, H.P.J., and J.V. Sharp (1978). *The Structural Engineer, 56A*, 69-76

Valiente, A. (1980). *Ph.D.Thesis*. Universidad Politécnica de Madrid, Madrid. (Spain).