Fatigue behaviour of wire ropes

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This paper presents a model for the analysis of the fatigue behaviour of strands and cables. It is assumed that this behaviour may be derived from that of individual wires. The results of the model are compared to test results performed on wires and strands of different diameter, geometry, spin angle and chemical composition. Some recommendations based on the research performed are proposed for improving the fatigue behaviour of strands.

1. INTRODUCTION

Wire ropes are widely used in dynamically loaded structures such as cable-stayed bridges or suspension bridges. The design of bridges with greater slenderness and longer spans means that the fatigue life of cables has become one of the critical parameters of the structure.

The classical method used to determine the fatigue properties of cables is based on the obtention of Wöhler's curves and all the standard requirements are specified in that way [1–3]. Such curves illustrate the number of cycles N up to rupture as a function of the load amplitude $\Delta P = P_{\text{max}} - P_{\text{min}}$, where $P_{\text{max}}$ and $P_{\text{min}}$ are maximum and minimum values of the load in a cycle. The final result of a fatigue test programme is a family of curves $\Delta P-N$ for different values of $P_{\text{min}}$.

The classical method involves serious disadvantages for the study of the fatigue behaviour of cables. Firstly, the achievement of Wöhler’s curves is costly: the obtention of each curve requires very often performing between 30 and 60 tests [4, 5], some of them with long duration, because near the fatigue limit the cable may withstand millions of cycles without rupture. Secondly, the results obtained cannot be applied directly to other materials or other geometries of cable (different number of wires, different diameter, different pitch). Finally, the most important objection to Wöhler’s curves is based on its phenomenological character which does not allow one to determine the causes of fatigue fracture. Therefore, test results do not provide indications to the producer about methods of improving the fatigue behaviour of cables.

With the application of fracture mechanics, the analysis of physical phenomena governing the nucleation and propagation of a fatigue crack in metals has been possible. The deeper knowledge achieved has allowed the improvement of fatigue behaviour of metals and alloys. Such study has already been carried out for the prestressed steel wires constituting strands, and a model has been proposed for predicting both the fatigue life and the fatigue limit of these wires [6, 7].

This paper presents an expansion of the model proposed for wires for the analysis of the fatigue behaviour of cables, a more frequent case in civil engineering structures. It is assumed that the fatigue behaviour of strands may be derived from that of individual wires. The load distribution between the different wires may be computed by taking into account several factors (strand geometry, pitch, wire diameters, etc.). The results of the model are compared with test results performed on wires and strands of different diameters and chemical compositions. Finally, some recommendations based on the research performed are proposed for improving the fatigue behaviour of strands.

2. A FRACTURE MECHANICS APPROACH TO THE FATIGUE OF STEEL WIRES

The process of rupture of a steel wire by axial fatigue can be divided into two stages: the nucleation of a surface flaw and its propagation up to a critical size for which fracture of the wire takes place. Between the two stages there is a transition regime in which the mechanisms controlling each stage are operative at the same time, this transition being called the short cracks regime [8].

The fatigue life $N$ (number of cycles) of a wire subjected to a constant-amplitude cyclic load will be given by

$$N = N_i + N_{sc} + N_p$$

where $N_i$ is the number of cycles required for surface microcrack generation, and $N_{sc}$ and $N_p$ are the number of cycles for propagation of the microcrack and the crack, respectively, up to the critical size.

Previous researches have shown that fatigue ruptures were always initiated at surface flaws with depths between 25 and 125 $\mu$m [6, 9]. In all cases small cracks were
observed at the bottom of these flaws, probably produced during the drawing process [7]. These observations lead to the assumption that the crack initiation period \( N_i \) may be neglected, because cracks were present before starting the fatigue process [6, 7].

With respect to the crack propagation stage, it has been shown experimentally that the crack growth rate follows the Paris law

\[
\frac{da}{dN} = C(R)(\Delta K)^m(R)
\]

where \( a \) is the crack depth, and this \( da/dN \) is the crack growth rate per cycle, \( \Delta K \) is the stress intensity range defined below and \( C(R) \) and \( m(R) \) are experimental coefficients dependent upon the stress ratio \( R \), defined as the ratio between the minimum and maximum stress in a cycle \( (R = \sigma_{\text{min}}/\sigma_{\text{max}}) \), but independent of crack depth, mean stress in a cycle and frequency [10]. Fig. 1 illustrates experimental plots of \( da/dN \) against \( \Delta K \), showing those results. For crack growth rates below \( 10^{-9} \) m cycles\(^{-1}\), a threshold value of the stress intensity range \( \Delta K_{\text{th}} \) has been observed, below which crack growth was undetected. The threshold stress intensity range is dependent upon the stress ratio \( R \), the following empirical relationship being obtained [10]:

\[
\Delta K_{\text{th}} = 5.54 - 3.43R
\]

where \( \Delta K_{\text{th}} \) is expressed in MPa m\(^{1/2}\).

The microcrack propagation stage is more difficult to analyse. The details of the theoretical and experimental research performed have been previously published [6, 7]. The results of the research show that according to the similitude principle between long and short cracks [11], equations 2 and 3 apply for the analysis of fatigue microcrack growth behaviour by changing the expression utilized to determine the stress intensity factor \( K \), taking into account the effects of the vicinity of the free surface, the variation of the crack shape during its propagation and the surface residual stresses.

3. THEORETICAL MODEL FOR THE ANALYSIS OF FATIGUE BEHAVIOUR OF WIRE ROPES

From the results outlined above, a model has been developed for predicting the fatigue behaviour of cables, strands and steel wires. It is assumed that a cable or a strand has failed when a single wire has fractured, although the fracture of the whole rope had not yet happened.

Initial data for application of the model are as follows: the maximum and minimum stress in the direction of the axis of each wire, the depth \( a_0 \) and shape of the surface flaw, the crack depth \( a_t \) for which the short crack and the long crack behaviours coincide, and the depth \( a_c \) and shape of the critical crack.

Stresses in the direction of the axis of each wire are higher than the quotient of the load and the nominal cross-section of all wires of a cable due to the helical spinning of the wires. The value of the stress on a wire placed on the \( j \)th layer of a strand has been obtained by Hansel and Olesky [12] and is given by

\[
\sigma_j = \frac{P \cos^2 \alpha_j \cos \beta}{n \sum_{i=1}^{n} \Omega_i \cos^3 \alpha_i}
\]

where \( n \) is the number of strands in the cable, \( \beta \) is the angle between the axis of the strand and the axis of the cable, \( i \) is the number of layers of wires in each strand, \( \Omega_i \) is the cross-section of all wires in each layer, and \( \alpha_i \) is