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Design S-N Curves for Axial Fatigue of Spiral Strands

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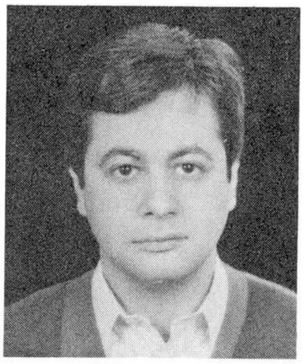

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Summary

Based on an extensive series of theoretical parametric studies on some very substantial spiral strands with realistic construction details, a new set of S-N curves for predicting the axial fatigue life of spiral strands to first outer (or inner) wire fractures have been proposed. The theoretical model based on which these parametric studies are conducted, has been verified extensively against a very large number of carefully conducted and large-scale test data using specimens with diameters ranging from 25 to 164mm, as produced by different manufacturers and tested by a number of Universities/Research Institutions. The proposed S-N curves are compared with others recommended by API, Chaplin, and Tilly, which are the ones that are currently most commonly referred to and certain shortcomings of previously available recommendations by others are identified.

1. INTRODUCTION

In recent years there has been considerable interest in the tensile fatigue of wire ropes (and spiral strands) for use in both offshore and onshore applications. On the offshore scene, there has been a growing need for longer and stronger elements with larger diameters for use as components in mooring systems for oil exploration, production, and accommodation platforms. As regards onshore structural applications, steel cables are extensively used in bridges and as tension elements for suspended and stayed structures generally.

With the increasing number of available large scale test data for a wide variety of cable constructions, design S-N curves for steel cables have been included in some recent codes of practice in the field of Structural Engineering. One example is API (American Petroleum Institute) recommended S-N curve, another the design S-N curves currently in preparation for the Health and Safety Executive by the Transport Research Laboratories, U.K. Work is also in progress for Eurocode 3. The API and HSE attempts at codifying the S-N curves have taken the form of suggesting lower bound curves to published S-N data with no due attention paid to the specific cable construction details and detrimental termination effects of test specimens which can both be of prime importance.

The present paper presents newly developed S-N curves which take the construction details of large diameter (i.e. realistic) spiral strands into account, and also cater for the effects of end terminations. The proposed S-N curves are based on extensive theoretical parametric studies using a newly proposed model. Finally, the proposed S-N curves are compared with others recommended by API, Chaplin, and Tilly, which are the ones that are currently most commonly referred to, and it is shown that in certain cases, these S-N curves provide unconservative results. As a pre-requisite to this, however, a brief description of the theoretical model follows next, which will, then, enable the reader to better understand (and appreciate) the results presented later.

2. THEORY

Using the orthotropic sheet model (1) it is now possible to obtain reliable estimates of interwire contact forces (and stresses) throughout multi-layered helical strands. Experimental observations suggest that individual wire failures are largely located over the trellis points of interlayer contact and it is now believed that this is as a result of high stress concentration factors in these locations.

Once the maximum effective Von-Mises stress, $\bar{\sigma}'_{max}$, over trellis points of contact, for a given mean axial load on the strand is calculated, the stress concentration factor, K_S, is defined as

$$K_S = \frac{\bar{\sigma}'_{max}}{\bar{\sigma}'} \quad (1)$$

where $\bar{\sigma}'$ is the nominal axial stress in the helical wires which may be calculated using the method developed by Raoof (1).

Raoof (1) deals with the topic of strand axial fatigue at some length. Using the so-obtained values of K_S in conjunction with axial fatigue data on single wires, a theory has been developed which predicts the axial fatigue life of strands (under constant amplitude cyclic loading) from first principles.

For carbon steel wires the fatigue stress-number of cycles plot (S-N curve) possesses an endurance limit, S′, below which no damage occurs. Traditionally the magnitude of S′ is compared to the ultimate wire strength, S_{ult}: tests on single galvanised wires suggest an approximate value of S′ = 0.27 S_{ult}. The reduced magnitude of the endurance limit, S_e, which takes interwire contact and fretting plus surface conditions and size effects, etc., into account may be defined as

$$S_e = K_a K_b S' \quad (2)$$

where, $K_b = \frac{1}{K_s}$, and K_a is a constant.

The so-obtained values of the parameters S_e, then, are used to produce the S-N curves for fatigue life to first outer (or inner) wire fractures in spiral strands using the S-N curves available in the literature for axial fatigue life of individual wires of a given grade (1).

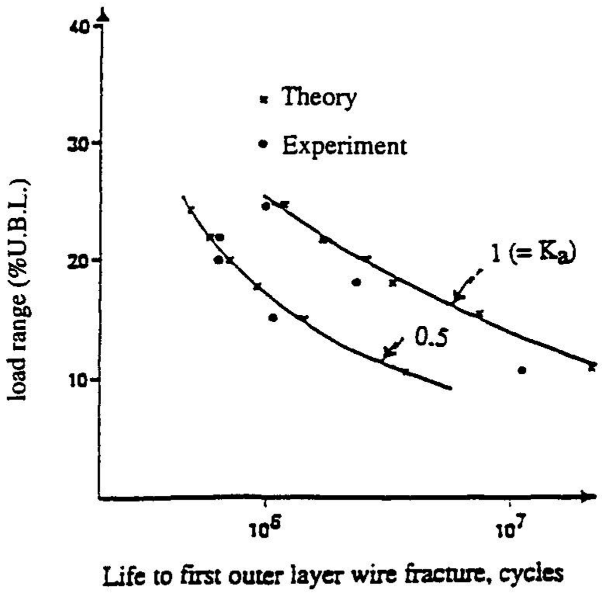

Fig. 1 Axial fatigue of 51mm O.D. strand-comparison of theory and test data.

Fig. 1 compares the theoretical predictions with experimental data for a 51mm diameter spiral strand. The criterion for fatigue initiation has been the occurrence of first wire failure in the outer layer. A fairly significant degree of scatter was found in the experimental data which may be covered by an empirical surface finish factor K_a in the range $0.5 \leq K_a \leq 1.0$. The ultimate tensile strength of the wire material is $S_{ult} = 1640$ N/mm^2. With the strands having epoxy resin end terminations, all the initial wire failures in this strand occurred away from the ends. However, as discussed elsewhere (2), for the end terminations to have no detrimental effects on the wire fractures remote from the ends the minimum length of test specimens must be around 10 lay lengths with the wire fractures occurring within the central region which extends by 2.5 lay lengths on either side of the middle of the test specimen (i.e. within the central portion with a length of 5 lay lengths). It then follows that due to the total length of the tested 51mm O.D. strands being significantly less than 10 lay lengths, even for the wire fractures away from the ends, certain test data points in Fig. 1 have been influenced by the detrimental end effects with the correlations between the theory and such test data suggesting $K_a = 0.5$ as an appropriate factor in the presence of end effects. Otherwise, for wire fractures which happen away from the ends and, in addition, are not influenced by end effects, one may assume $K_a = 1.0$: this, then, provides the reader with an insight into the role of the parameter K_a in the proposed theoretical model.

The theoretical predictions have been supported by a very extensive set of large scale test data relating to spiral strands with diameters equal to 25, 35, 39, 40, 44, 51, 53, 63, 100, 127, and 164mm as produced by different manufacturers and tested by Bridon Ropes, Imperial college, Transport Research Laboratories, and National Engineering Laboratories in U.K., and University of Alberta in Canada, with lay angles within the wide range $11^\circ \leq \alpha \leq 21^\circ$, and wire diameters covering the range $3mm \leq D \leq 7.10mm$, which very nearly embody the presently adopted manufacturing limits. In all cases, the correlations between the theoretical predictions and such an extensive set of large scale test data has been very encouraging. Space limitations do not allow a full reporting of such good correlations here: these have been reported fully in the references cited elsewhere (3). This, then, provides ample support for the general applicability of the recently proposed theoretical model which can predict both initial outer and/or inner wire breakages with the initial inner wire fractures generally having a lower fatigue life than the outer wires (1).

3. THEORETICAL PARAMETRIC STUDIES

3.1 Background

Recently, Bridon Ropes made the construction details for three realistic types of 127mm diameter spiral strands available to the present author. In particular, three different levels of lay angles (12°, 18° and 24°) were used for designing these strand constructions with each strand having the same lay angle in all its layers and their other geometric factors (such as number and diameters of the helical wires) were kept very nearly the same. As discussed elsewhere (3) following extensive theoretical and experimental work, the lay angle has been found to be the primary factor which controls a number of strand overall structural characteristics with the other geometrical factors being of secondary importance. It should be emphasised that the 12-24 degrees range of presently adopted lay angles cover the full practical range of this parameter as currently used by cable manufacturers. Ref. (3) gives the construction details for 127mm diameter spiral strands used in the following theoretical parametric studies. The assumed Young's modulus for galvanised steel wires $E = 200\ kNmm^{-2}$ and the Poisson's ratio for wire material $\vartheta = 0.28$. The Ultimate Breaking Load (U.B.L.) of the strands was assumed to be the same, equal to 13510 kN, while tensile ultimate strength of the wire material $S_{ult} = 1520$

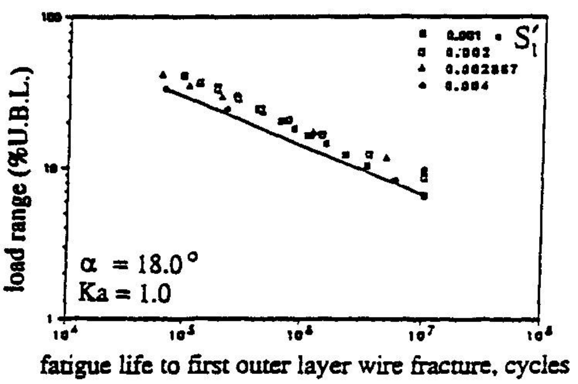

Fig.2
Theoretical effects of changing S_1' on axial fatigue life for a given lay angle, α.

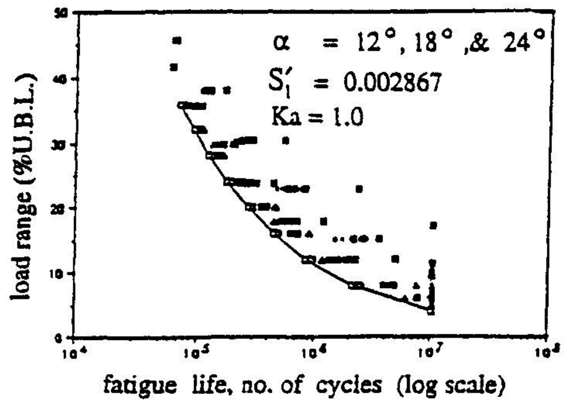

Fig.3
Theoretical effects of changing α on axial fatigue life for a given S_1' .

Nmm^{-2}.

For the purposes of theoretical parametric studies, four values of strand mean axial strains S_1' = 0.001, 0.002, 0.002867, and 0.004 were assumed which cover the usual practical working ranges for structural applications. Axial fatigue life was defined as the number of cycles to first wire fracture.

3.2 Design Recommendations

Fig. 2 presents (as a typical example) the plots (in log-log scale) of load range (as a percentage of U.B.L.) against axial fatigue life to first outer layer wire fracture for the 127mm diameter spiral strand with a lay angle of 18 degrees. The assumed value of K_a for this figure is 1.0 - i.e. the initial wire fractures are assumed to happen in the free field and are not affected by end terminations. The plots cover a wide range of $0.001 \leq S_1' \leq 0.004$. This figure includes a lower bound straight line to all the individual theoretical data points which compared to those in Fig. 3 are found to exhibit a much less degree of scatter. The composite data points in Fig. 3, on the other hand, relate to all the three types of 127mm diameter spiral strands with the lay angles of 12, 18, and 24 degrees and K_a = 1.0 (although, only one value of S_1' = 0.002867 has been assumed for all the results in this figure and changing the value of S_1' will cause significantly more degree of scatter in the results). Comparing the scatter of results in Fig. 2 with those in Fig. 3, therefore, strongly suggest the merits in separating the results for each individual value of lay angle: in this way, much more sensible lower bound S-N curves may be obtained with the individual data points relating to each lower-bound S-N curve exhibiting reasonable degrees of scatter. The above exercise may, therefore, be repeated for other cases of practical importance: (a) when K_a = 0.5 -i.e. when individual wire fractures are assumed to be affected by the end terminations; and (b) when the criteria for fatigue failure is changed to that corresponding to the other extreme condition - i.e. when fatigue life is defined as the number of cycles to first wire fracture in the innermost layer of helical wires. In case (b), two separate sets of plots may be obtained: (ii) those with K_a = 1.0; and (ii) another set using K_a = 0.5. Space limitations do not allow presentation of all the plots for cases (a) and (b) in the above, here. Suffice it to say that in all cases, the scatter of the individual theoretical data points (to which a lower-bound S-N curve is added) is similar to those presented in Fig. 2.

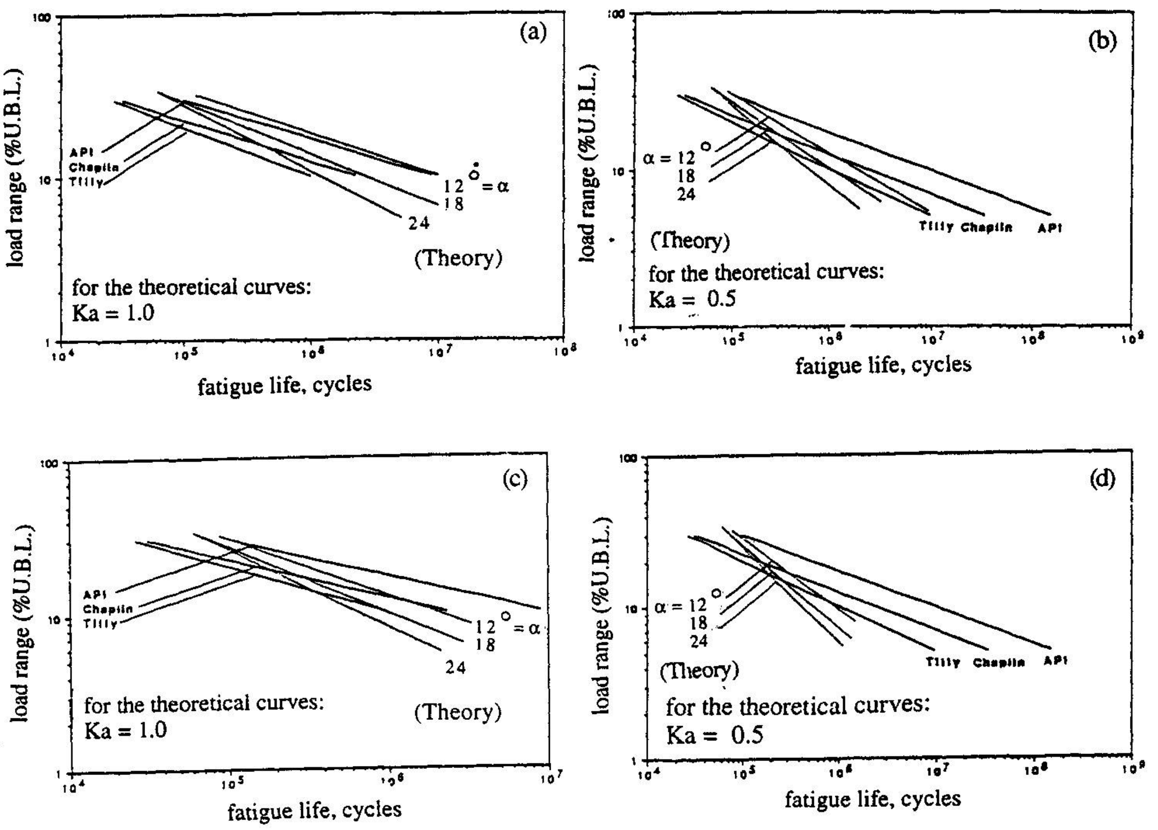

Fig. 4. Comparison of alternative design S-N curves for different values of K_a: (a) and (b) K_a = 1.0 and 0.5, respectively, for the fatigue life to first outer layer wire fracture; (c) and (d) K_a = 1.0 and 0.5, respectively, for the fatigue life to first wire fracture in the innermost layer.

Figs. 4a-d present all the so-obtained theoretical lower bound S-N curves. Figs. 4a,b correspond to the plots based on K_a values of 1.0 and 0.5, respectively, with the fatigue life defined as number of cycles to first outer layer wire fracture; while in Figs. 4c,d (which, again, assume K_a = 1.0 and 0.5, respectively), fatigue life is defined as the number of cycles to first wire breakage in the innermost layer. In each figure, three theoretical lower bound S-N curves corresponding to lay angles of 12, 18, and 24 degrees are presented and, considering that the plots are in log-log scale, the significant influence of lay angle on the axial fatigue life of spiral strands is obvious, with increasing values of lay angles in various layers leading to decreasing magnitudes of fatigue lives (for a given axial load range).

As mentioned previously, the assumed values of strand Ultimate Breaking Load (U.B.L.) and grade of wire for producing the theoretical lower bound S-N curves in Figs 4a-d are 13510kN and 1520 Nmm^{-2}, respectively. However, as discussed at some length elsewhere (3), because the strand axial load range in these plots is non-dimensionalized with respect to U.B.L., all the theoretical lower bound S-N curves are of general applicability irrespective of the magnitude of U.B.L. and grade of wire in practice. Included in Figs. 4a-d are also lower bound empirical S-N curves recommended by API (4), Chaplin (5), and Tilly (6), which are the ones most commonly referred to in the available literature. In producing these purely empirical S-N curves non of these references have differentiated between various types of strand (or, indeed, rope) constructions used in their experiments. Moreover, different types of failure criterion have been adopted by these references: the failure criteria adopted by Chaplin is number of cycles to total collapse, while Tilly has chosen number of cycles to 5% wire fracture (i.e. life to fatigue initiation). The failure criteria chosen by API is not defined in the code, and there does not seem to be any background literature (available in the public domain) for this recommendation.

The potentially unsafe nature of the previously reported lower bound S-N curves of API, Tilly, and Chaplin for certain (i.e. smaller) levels of axial load range (depending on the magnitude of lay angle), as shown in Figs. 4a-d, is noteworthy. One thing is clear: the API recommended S-N curve can be unconservative for certain practical cases. As regards Tilly's or Chaplin's recommended S-N curves, the situation depends on the failure criteria adopted in practice, and the magnitude of the lay angle for the wires of the strands which are to be used in a given construction. In this context, one should also decide as to whether fatigue failures are to happen at (or in the vicinity) of end terminations or in the free field, away from the ends.

4. CONCLUSIONS

Using extensive theoretical parametric studies (based on a fully verified theoretical model) on some substantial (large diameter) multi-layered spiral strands with realistic construction details and covering the full manufacturing limits of lay angles which are the primary (controlling) parameter, a set of design S-N curves for axial fatigue life prediction of spiral strands are proposed. Unlike previously available and purely empirical S-N curves, the present recommendations cater for the influence of changes in lay angles on the strand axial fatigue life and also can account for the detrimental termination effects. Comparisons are made between the presently recommended design S-N curves and those recommended by others, and the previously available S-N curves are found to suffer from certain shortcomings.

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