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Interwire Contact Forces and Behaviour of Spiral Strands

Forces de contact entre fils et comportement général des brins en spirale

Kraftübertragung zwischen Drähten in gedrillten Litzen

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SUMMARY
The importance of catering for the effect of interwire/interlayer contact patches on various spiral strand overall characteristics is briefly discussed. Simple guidelines are given for carrying out appropiate single (or thin) wire fretting fatigue experiments for predicting and/or improving spiral strand fatigue performance.

RÉSUMÉ
L'effet de surface de contact entre fils et couche sur l'ensemble des caractéristiques des divers brins en spirale est présenté. Des directives simples sont données pour effectuer des essais fatigue due au frottement des fils simples (ou doubles) permettant de prédire et/ou d'augmenter la performance optimale due à la fatigue des brins en spirale.

ZUSAMMENFASSUNG
Die Verhaltensmerkmale gedrillter Litzen sind stark von den unterschiedlichen Kontaktverteilungen zwischen den Drähten oder Drahtlagen abhängig. Wie gezeigt wird, können nach einfachen Richtlinien Reibermüdungsexperimente an Einzel- oder Doppeldrähten durchgeführt werden, um das Ermüdungsverhalten gedrillter Litzen vorherzusagen oder zu verbessern.

1. INTRODUCTION

Over the last thirteen years, a substantial effort has been put by the present author and his associates into assessing contact forces and the associated relative displacements between individual wires, taking full account of frictional effects, in large and multi-layered spiral strands undergoing a wide variety of loading regimes. This has been achieved by employing the orthotropic sheet concept based on which the individual layers of helical wires in a spiral strand have been modelled as a series of partly self-prestressed orthotropic cylinders which structurally interact. Thus each layer of wires, although discontinuous, has its elastic properties "averaged" in a way familiar in the analysis of stiffened plating for bridge decks and ship hulls. Results from contact stress theory are used to determine the properties of the orthotropic sheets, whose principal axes run parallel and perpendicular to the individual wire axes. The chief advantage of this approach is that its accuracy improves as the number of wires in a given layer increases; i.e. for practical wire sizes, as the size of spiral strand grows. This desirable situation may be contrasted with the decreasing accuracy and increasing complexity as the number of wires increases associated with certain previously available methods of analysis which have primarily been developed for frictionless wires. Space limitations do not permit a detailed review of the available literature on various aspects of wire rope behaviour. The interested reader may refer to fairly recent surveys of Utting and Jones (1), Costello (2) and Chaplin and Potts (3) for further information. For the present purposes, much attention will be devoted to the application of the orthotropic sheet theory to steel cables.

2. MODELS BASED ON THE ORTHOTROPIC SHEET CONCEPT

For a given mean axial load, the orthotropic sheet approach yields estimates of axial (4), torsional (5) and free bending (6) stiffnesses, which are found to be functions of the applied axial, torsional, and free bending load perturbations, respectively. The stiffnesses for small load changes can be much larger than for large load perturbations, because sufficiently small disturbances do not induce interwire slippage. The theoretical models for various loading regimes predict the bounds to the stiffnesses and describe the variation between them.

It is now possible to predict the energy dissipation under continued uniform cyclic axial, torsional and free bending loading by assessing the energy dissipation per cycle on each of the contact patches within the strand: summation yields a value for overall hysteresis of axially preloaded spiral strands (5, 6, 7).

Once fatigue is addressed, the number of variables involved makes effect of mean axial load, and grade of wire have been investigated theoretically.

To extend the present analytical model to cater for the effect of sea-water corrosion, Equation (7a) may be rewritten as (16).

$$S_e = K_c\ K_a\ K_b\ S' \tag{8}$$

where K_c is a parameter defined as the ratio of single wire fretting fatigue endurance stress in air to the corresponding reduced value of stress in sea-water at a fatigue life of $N_c = 10^7$ cycles. For example, for small diameter (1.5-2.5mm) wires, data from Takeuchi and Waterhouse (18) and Thorpe and Rance (19) suggest that $K = 0.7$. Cable S-N curve under sea-water corrosion may thus be estimated by using Equation (8) instead of Equation (7a) which assumes $K_c = 1$ for in-air conditions. Otherwise, the calculation procedure is the same as the corresponding in-air condition. Fig. 2 presents a theoretical comparison of in-air and in-sea-water outer layer axial fatigue lives for a 45mm diameter spiral strand (13). The plots cover K_a values in the range $0.5 \leq K_a \leq 1.0$, while the K_c values for in-air and in-sea-water are 1.0 and 0.70, respectively. An examination of the theoretical results provides an explanation for the previously reported experimental observations (15) in which no marked reduction in axial fatigue life (cf. in-air data) due to the presence of sea-water is reported: the usual degree of scatter in-air fatigue lives covered by $0.5 \leq K_a \leq 1.0$ may easily mask the rather smaller reduction in life due to sea-water corrosion as simulated under laboratory conditions.

For an elliptical contact patch carrying a constant normal force, P, and a monotonically increasing torque, M, the torque causes the spread of an annular region of slip from the outer edge of the contact towards the centre of the patch, until adhesion is completely lost and gross sliding takes place. Raoof (8) has used such results in the field of contact stress theory to determine the ratio a*/a, where a = semi major axis of the individual trellis contact patches which under partial slip conditions possess a no-slip part whose semi-major axis is a*, Fig. 3. This figure shows variations of a*/a of the individual trellis points of contact as a function of cable axial load perturbation for two different levels of mean axial load on a 39mm spiral strand with an ultimate tensile strength of 0.123MN and whose outer layer is layer number 1. Fig. 3 illustrates that for the practical ranges of axial load perturbations, the spread of the partial slip zone over the trellis points of contact is not very significant. Indeed, it is demonstrated that gross sliding is unlikely to occur. On the other hand, theoretical results (backed by experimental observations) strongly suggest that gross sliding over the line-contacts between various wires in any given layer start at much lower levels of range to mean ratio of axial load on the cable (7). The principal source of strand overall hysteresis is, therefore, the interwire

It is not the intention to repeat the often lengthy analytical derivations and/or experimental techniques here, nor, indeed, does space permit such repetition. In view of their prime importance, the following sections give an account of the controlling role of the pattern of contact patches on cable fatigue performance.

3. INTERWIRE/INTERLAYER CONTACT PATCHES

3.1 Background

Full details of the various patch compliances are given elsewhere (4) and it is useful to review some phenomena associated with contact patch behaviour. Two classes of interwire contact occur in a multi-layered spiral strand. The first, which governs the overall axial, torsional, and free bending (i.e. in the absence of sheaves, fairleads, or other formers) stiffnesses, and associated hysteresis under cyclic loading, is the contact within a given layer between adjacent "parallel" wires. In terms of contact stress theory, this case can be regarded as the line-contact of parallel cylinders. The second class, which is less important for the above strand stiffnesses and associated hysteresis but which play a central role in fatigue phenomena, involves the contact between wires in different layers at the "trellis" points.

Taking cyclical axial loading (on a strand whose ends are not allowed to rotate) first, the line-contacts within a layer (class 1) clearly experience a cyclical variation of the direct normal force on the contact as a result of the variation in the clench forces on the layer caused by the changing axial load. Each line-contact patch also experiences a varying shear force which tends to cause sliding of one cylinder parallel to the other, as a consequence partly of the tendency of the lay angle to decrease in association with the increase in cable axial strain, S'_1, and partly due to the induced axial strain in individual wires, S_1, where, it can be shown that (14)

$$\frac{S^i_1}{S'_1} = 1 - 0.00255\alpha_i + 0.000215\alpha_i^2 - 0.000027\alpha_i^3 \qquad (1)$$

$$0 \le \alpha_i \le 25^\circ$$
$$S'_1 \le 0.005$$

where, the lay angle in layer i, α_i , is expressed in degrees, and S^i_1 is the wire direct strain in layer i.

The tensorial shear strain, S^i_{6T} , over the line-contact patches in layer i is given by (14).

$$S^i_{6T} = S'_1 \, F\,[\alpha_i] \qquad (2a)$$

where

$$F[\alpha_i] = 0.0196\alpha_i - 0.000394\alpha_i^2 + 0.0000247\alpha_i^3 \quad (2b)$$

Using Equations (2a) and (2b), the magnitude of interwire line-contact slippage, u_i, in layer i, whose wire diameter is D_i, is given as

$$u_i = 2D_i\ S^i{}_{6T} \quad (3)$$

The change in the lay angle, $d\alpha_i$, in layer i, as a function of the lay angle, α_i, and cable axial strain, S'_1, may simply be obtained from (14).

$$\frac{d\alpha_i}{S'_1} = 0.0203\alpha_i + 0.000576\alpha_i^2 - 0.0000395_i^3 \quad (4)$$

$$0 \le \alpha_i \le 25°$$
$$S'_1 \le 0.005$$

where, $d\alpha_i$ and α_i are expressed in radians and degrees, respectively.

The interwire/interlayer relative rotation, $d\omega_i$, over the trellis points of contact between layers i and i+1, is then given as

$$d\omega = |d\alpha_i| \pm |d\alpha_{i+1}| \quad (5)$$

where, the positive sign holds for the case when the two adjacent layers have opposite lay.

Simple routines for obtaining the magnitude of normal forces on the line and trellis contact patches have, on the other hand, been presented elsewhere (4). However, it transpires that Eq. (19) in Ref (4) should be replaced by

$$X_{Ri} = X_{MSi} - 2P_{Msi}\ \cos\beta_i$$

Note that all the results presented in various papers of the present author to date are based on the above Equation rather than Equation (19) in Ref (4).

The above information is of direct relevance as an input to interwire fretting fatigue experiments aimed at improving cable fatigue life. Such data should also prove rather useful in the context of tests between individual wires with different types of lubrication in order to determine the relative efficiency of various lubricating compounds under a variety of interwire fretting conditions such as those occurring inside an axially preloaded spiral strand as discussed in the next section.

3.2 Fretting fatigue phenomena and strand fatigue performance

The fretting problem is an extremely difficult one and, in the absence of relevant experimental data, it is not easy to draw any reliable conclusions from purely analytical techniques. Nevertheless, careful examination of the literature in the general field of fretting fatigue, coupled with available contact stress theories and load-displacement values such as those discussed in the previous section, should help to design (and, later on interpret the results of) interwire fatigue tests aimed at predicting and/or improving cable fatigue performance. A fairly recent account of available fretting fatigue results for individual wires such as those reported by, say, Waterhouse and his associates is presented by Chaplin and Potts (15). For the present purposes, a few introductory remarks may give a feeling for the complexities involved and is hoped to provide a few clues as how to tackle the problem of cable fatigue performance.

Fairly recently, the present author reported theoretical models for predicting axial and restrained bending fatigue life of axially preloaded spiral strands from first principles (8, 9). In both cases, it has been shown that it is the state of contact stresses over the trellis points of contact which primarily control cable fatigue life, although the modes of trellis contact displacements in the context of axial and bending loading regimes are very different: this is briefly discussed in the following sections in which the need for further fretting fatigue experiments employing realistic values and modes of contact forces and relative displacements, is emphasized.

3.2.1 Axial fatigue

The orthotropic sheet theory has been used for obtaining estimates of interwire/interlayer contact stresses throughout realistic pre-tensioned multi-layered structural strands. These data have been used to obtain estimates of the maximum Von-Mises contact stresses, σ_{max}, on the individual elliptic trellis (interlayer) contact patches. For each individual trellis contact patch, a stress concentration factor is defined as

$$K = \frac{\bar{\sigma}_{max}}{\bar{\sigma}} \qquad (6)$$

where $\bar{\sigma}_{max}$ is the maximum Von-Mises stress at a given strand mean axial load which occurs at a depth z below the surface of contact patch central axis, and $\bar{\sigma}$ is the corresponding mean nominal axial stress in the individual wires due to strand tension.

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 (8). The theoretical interlayer slippage over the individual points of contact between various layers has also been addressed which takes interwire friction into account.

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 (8) as:

$$S_e = K_a K_b S' \tag{7a}$$

where (13)

$$S' \approx 0.27 S_{ult} \tag{7b}$$

In the above, K_a = surface finish factor, and $K_b = 1/K_s$, with S_{ult} = ultimate wire stress, and S' = wire endurance limit.

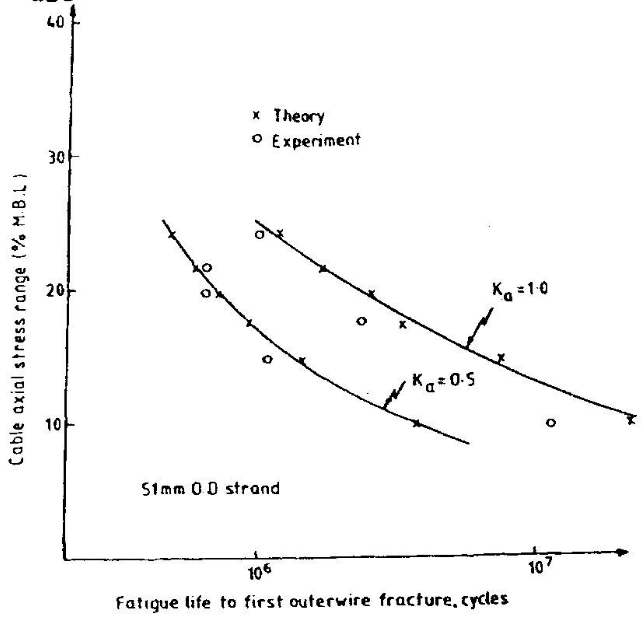

Fig.1 Comparison of theoretical and experimental axial fatigue S-N curves

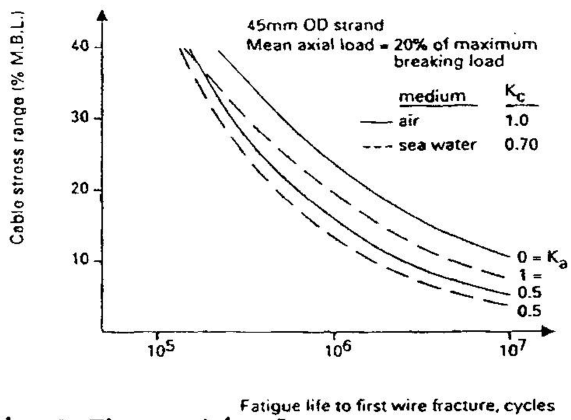

Fig.2 Theoretical comparison of in-air and in-sea-water S-N curves

Figure 1 compares the theoretical axial fatigue life predictions with experimental data on a 51mm diameter spiral strand. The criterion for fatigue initiation has been the occurrence of first wire failure in the outer layer. With epoxy resin end terminations, all the wire failures occurred away from the ends (in the free field). A fairly significant degree of scatter was found in the experimental data which may be covered by empirical finish factor K_a in the range $0.5 \leq K_a \leq 1.0$. similar encouraging correlations using $K_a = 0.5$ have been found between experimental data and theory on a 39mm diameter strand (8) and Tilly's (17) experimental data (16). The theory indicates that internal wire fractures invariably occur prior to external wire fractures. Moreover, other effects such as those due to the effect of mean axial load, and grade of wire have been investigated theoretically.

To extend the present analytical model to cater for the effect of sea-water corrosion, Equation (7a) may be rewritten as (16).

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where K_c is a parameter defined as the ratio of single wire fretting fatigue endurance stress in air to the corresponding reduced value of stress in sea-water at a fatigue life of $N_c = 10^7$ cycles. For example, for small diameter (1.5-2.5mm) wires, data from Takeuchi and Waterhouse (18) and Thorpe and Rance (19) suggest that K = 0.7. Cable S-N curve under sea-water corrosion may thus be estimated by using Equation (8) instead of Equation (7a) which assumes $K_c = 1$ for in-air conditions. Otherwise, the calculation procedure is the same as the corresponding in-air condition. Fig. 2 presents a theoretical comparison of in-air and in-sea-water outer layer axial fatigue lives for a 45mm diameter spiral strand (13). The plots cover K_a values in the range $0.5 \le K_a \le 1.0$, while the K_c values for in-air and in-sea-water are 1.0 and 0.70, respectively. An examination of the theoretical results provides an explanation for the previously reported experimental observations (15) in which no marked reduction in axial fatigue life (cf. in-air data) due to the presence of sea-water is reported: the usual degree of scatter in-air fatigue lives covered by $0.5 \le K_a \le 1.0$ may easily mask the rather smaller reduction in life due to sea-water corrosion as simulated under laboratory conditions.

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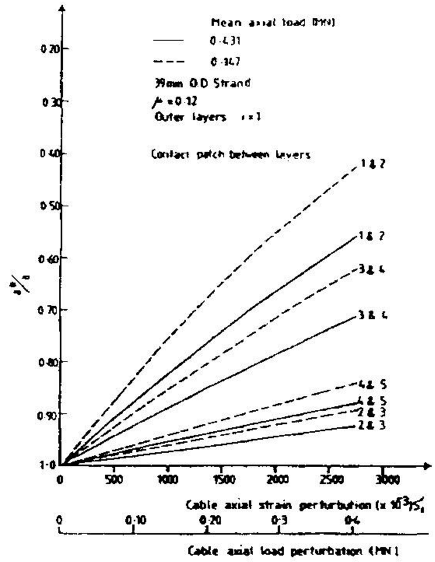

Fig.3 Spread of partial-slip zones in various trellis contact patches in a 39mm O.D. strand

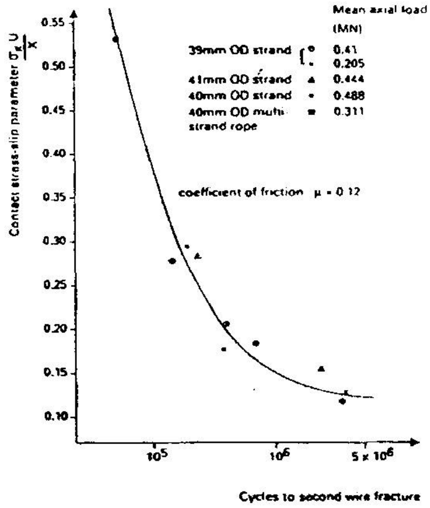

Fig.4 Plot of contact stress-slip parameter against restrained bending fatigue life for a number of steel cables

3.2.2 Restrained bending fatigue

There is surprising little information available on fatigue performance of spiral strands in free bending. The majority of published work concentrates on the influence of pulleys and sheaves as sources of wear and fatigue damage. Turning to the question of bending fatigue close to the termination, some experimental results (20) for a 39mm strand are of interest. In these tests, the initial wire breaks invariably occurred not near the extreme fibre but close to what would be regarded as the neutral axis in a rigid rod. This position can be shown, theoretically and experimentally (21), to be the location where the slip between the outer and penultimate layers of wires is largest. Thus interwire or rather interlayer fretting has been assumed to be the most likely cause of wire breakages, and to be much more relevant to a discussion of fatigue life than the traditionally assumed maximum wire stresses near the extreme fibres (6).

In detail, the life to second wire fracture (the second wire being approximately 5% of the outer layer wires, a popular but by no means universally accepted indication of incipient overall failure) was compared with the maximum wire stresses found in the author's experiments and calculations (22). A weak correlation was found in that it was possible to sketch curves through the data points - but the curves for each mean strand axial load were well separated.

A newly developed alternative, Fig. 4, appears much more promising. Here, the life to second wire fracture is plotted against a parameter linking

(i) the computed maximum tensile stress, σ_x, at the trailing edge of the interlayer contact patch between wires of opposite lay; i.e. at the edge of the so-called "trellis" contact,

(ii) The computed interlayer relative displacement, U, near the neutral axis at a distance equal to the interlayer contact patch spacing along the wire from the assumed ideally fixed end, and

(iii) the trellis contact patch spacing, x, along any individual wire in the outer layer.

The stress, σ_x, computed on an elastic basis, has been chosen in view of its likely role in fatigue crack initiation in the individual wires; cracks are commonly found at this location. The value of, U, near the neutral axis is taken since the slips (in the form of a sawing action as opposed to the rotational movements under the cable axial loading case) are largest there.

It is encouraging that the use of this parameter makes it possible to draw the single curve of Fig. 4 through the experimental data for a number of spiral strand constructions (9).

Finally, in view of the rather complex nature of the theoretical model, extensive theoretical parametric studies have been carried out for developing straightforward design formulations amenable to simple hand calculations (22).

3.2.3 Appropriate factors for realistic interwire fretting experiments

According to the above, the mode of interwire fretting for the strand bending fatigue at points of fixity is one of a sawing action at the trellis points of the interlayer contact patches as opposed to the torsional mode for the axial case. Theoretical studies suggest that for the average strand construction subjected to typical working axial loads, interwire fretting under restrained bending conditions appears to reach a significant level at rather large values of radii of curvature at the restrained socket. For example, for the 39mm diameter strand under a mean axial load of about 33% of the ultimate breaking load, interwire slippage between the outer and penultimate layers can reach the full-slip (gross-sliding) condition (i.e. relative interwire displacement ≈ 0.00085mm), well within the operational radii of curvature (of the order of 10-20 meters) at the restrained end. Full torsional slippage over the trellis points of contact is, however, very unlikely to occur in this same strand, once one addresses the axial fatigue problem. The use of the same modes of interwire contact deformation as those occurring inside spiral strands, in any interwire fretting experiment aimed at predicting and/or improving cable fatigue life is, therefore, strongly recommended. The appropriate levels of input parameters, such as the normal loads and relative deformations, for such experiments may now be realistically determined by the straightforward routines recommended in this paper.

Lubrication is an important factor in cable fatigue performance. In a number of previously reported twin wire experiments which have been carried out to identify the significance of various lubricants as regards cable fatigue performance, the range of input parameters such as magnitude of imposed normal forces and/or relative displacements have not been chosen with due regard given to those that are operative within realistic steel cables. Very often, the mode of interwire contact deformations have been determined by the ease of setting-up the testing equipment with little attention paid to adhering to the most appropriate modes of fretting movements as determined by the actual cable loading conditions. Future tests, however, should take such effects into account.

Finally, there is, at present, an ever increasing demand for larger diameter spiral strands outside the traditional range of cable diameters which tend to employ wire diameters up to, say, 8-9mm. There is currently very limited fretting fatigue data available on such large diameter wires. The majority of published axial fatigue S-N curves for bare wires have also been obtained on specimens with often much smaller diameters. Axial fatigue tests on larger diameter wires should, therefore, be carried out in order to identify possible size effects which may also affect the interwire fretting fatigue performance specially under sea-water corrosion conditions.

4. CONCLUSION

The controlling role of different classes of interwire/interlayer contact patches on various spiral strand overall characteristics is briefly discussed. In particular, the central role of interlayer (trellis) points of contact in the context of cable axial and restrained bending fatigue performance is emphasized in the light of the author's recent theoretical and experimental findings using well established results in the field of contact between elastic bodies.

It is suggested that single (or twin) wire fretting experiments should be carried out under realistic modes of interwire movements representative of the conditions inside steel cables. To this end, some straightforward formulations are presented which should prove useful in estimating the appropriate levels of normal loads and relative displacements to be adopted in such fretting fatigue experiments.

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