Journal of Constructional Steel Research 95 (2014) 256–262

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

The riddle of free-bending fatigue at end terminations to spiral strands

Mohammed Raoof [a,*], Timothy J. Davies PhD [b]

[a] Professor of Structural Engineering, School of Civil and Building Engineering, Loughborough University, Leicestershire, LE 11 3TU, United Kingdom
[b] Formerly, Research Student, School of Civil and Building Engineering, Loughborough University, Leicestershire, LE 11 3TU, United Kingdom

ARTICLE INFO

Article history:
Received 21 June 2013
Accepted 18 December 2013
Available online 26 January 2014

Keywords:
Spiral strands
Bending
Cyclic loading
Fatigue
Fretting fatigue
Bridges
Offshore platforms
Guyed masts

ABSTRACT

The importance of design against free-bending fatigue at points of end fixity to multilayered spiral strands used in various onshore and offshore structural applications is emphasised. A fairly extensive set of large scale test data covering a wide range of spiral strand construction details with the cables subjected to widely varying mean axial loads and bending amplitudes is used to critically examine the generality of the contact stress–slip versus fatigue life (S–N) model of Raoof which, unlike the traditional maximum bending stress models, takes the crucial effects of interlayer fretting on the strand free-bending fatigue life into account. The possible practical limitations of the Contact Stress–Slip approach are also discussed in some detail with much emphasis placed on the question of potential size effects associated with the free-bending design S–N curves.

1. Introduction

This paper is concerned with the free-bending fatigue performance of realistic multilayered large diameter spiral strands, Fig. 1. Such types of bending take place in the absence of sheaves or other formers, so that the radius of curvature of the strand is not predetermined. The pressing need to understand free-bending fatigue problems of helically wound cables in the field of structural engineering became apparent in the late 1970s. This was partly because of the need to replace the inclined hangers of the Severn suspension bridge, which was only opened around the mid-1960s, and partly because of the explosion of interest in deep sea oil exploration and production which necessitated the employment of the new generation of offshore platforms which were to be connected to the sea floor by large diameter helically wound steel cables (as discussed in a report for the U.K. Department of Energy [1]). Very briefly, free-bending fatigue problems are a source of concern in structures such as suspension and cable-stayed bridges, guyed masts and tethered buoyant platforms, where fatigue failures of steel cables near partially restrained terminations of various types are not uncommon. Moreover, back in 1988, Watson and Stafford [2] reported that inspection of a large number of cable-stayed bridges around the world had revealed occurrence of corrosion and fatigue problems around the anchor joints of cables. Indeed, it is now well established that free bending fatigue of axially preloaded helically wound steel cables near terminations, is a problem of considerable economic importance, and it has been an issue that has caused serious problems in suspension and cable-stayed bridge design, and more recently in the design of single point moorings used for holding, for example, storage tankers on station in an oilfield (e.g. [3,4]).

Fatigue tests on large diameter spiral strands are, however, so exceptionally expensive and the consequences of cable failure so alarming that the need for a theoretical model, capable of predicting the free-bending fatigue behaviour of spiral strands, based on a careful interpretation of the experimental results, was given a new urgency. To this end, back in the early 1980s, Raoof and Hobbs [5] reviewed the available literature on the free-bending behaviour of helically wound steel cables both in the free-field (i.e. away from the terminations) and also in the vicinity of the end terminations. These authors noted that, despite the efforts of many researchers, dating back to the early part of the 20th century, little progress had been made in this area. It was concluded that, with the previous work being almost entirely experimental in nature, the results could not be used to reliably predict the response of other spiral strands (much less a rope) unless a sound theoretical insight into the problem was achieved— hence, the work of Raoof and his associates in this area over the last thirty years or so, with a detailed summary of the salient features of their work given in Ref. [6].

There are, however, a number of still unresolved issues in this area which need clarification and some aspects of these form the subject of the present paper. As a prerequisite to this, the following section presents a brief description of the previous literature in this area with particular emphasis on the shortcomings of the previously available cable bending models and the attempts by Raoof and his associates to bridge the gaps in the state of knowledge as well as overcome the shortcomings of such models with their various degrees of sophistication (variation).

* Corresponding author at: School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom.

0143-974X/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jcsr.2013.12.006

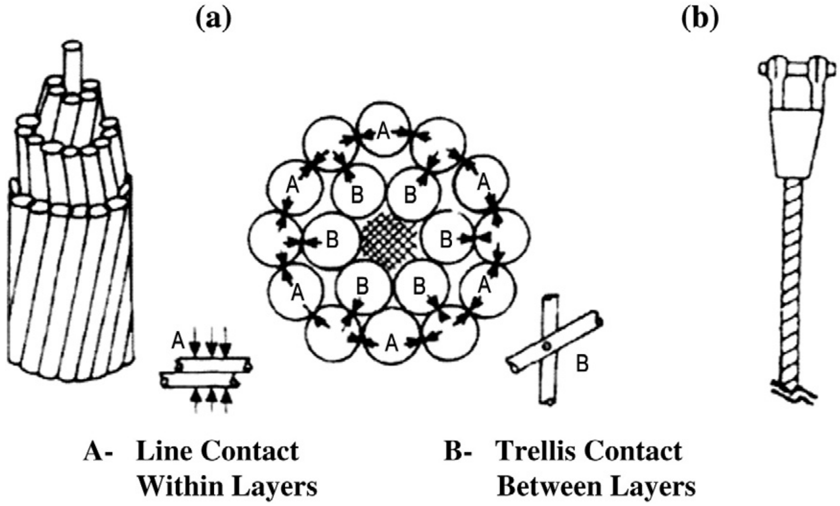

Fig. 1. (a) Interwire contacts in multi-layered spiral strands; (b) zinc-poured conical socket and spiral strand assembly used in the tests of Hobbs et al. [12] and Raoof [14].

2. Background

Chapman [7] was amongst the first to examine the bending stresses in helically wound steel cables, taking the helical nature of the wires into account. A simple (although not accurate) equation describing the bending of such cables was derived. Cyclic bending tests were also conducted which highlighted the significant effects of interwire friction. Since then, the models used to analyse the behaviour of spiral strands, or strands (in UK parlance) have improved markedly following the pioneering work of Hruska in the 1950s [8–10]. As regards the question of free 0bending in steel cables, on the other hand, to the best knowledge of the present authors, Wyatt [11] was the first to recognise the critical importance of cable bending stresses in the vicinity of points of restraint such as end terminations or cable clamping bands, etc. In his seminal paper, Wyatt [11] proposed an equation defining the bending deflection of a simple tendon (wire). In Wyatt's work, the variations of the stresses, induced by the lateral deflection of axially preloaded parallel wire steel cables used as the main cables in suspension bridges, were analysed.

Very briefly, the development of early models was traditionally based on the maximum bending strain (or stress) approach, which assumed that the strand's bending fatigue life was governed by the maximum bending strains (or stresses) which, using the concept of simple beam bending theory, occur at the extreme fibre position, which would, then, be the location where the initial wire fractures are expected to occur. In the late 1970s, Hobbs and Ghavami [12] carried out axial and free-bending experiments on two spiral strand constructions—a 16.4 mm and a 39 mm outside diameter (O.D.) spiral strand. The 39 mm test specimens were 7.40 m in length between the socket faces. In the in-line fatigue tests, on 16.4 mm and 39 mm strands, the wire failures appeared to be concentrated at the socket, with the first observed wire failures occurring in the outer layer. In the bending fatigue tests on the 39 mm O.D. strand, the wire failures also appeared to be concentrated at the socket, but the first observed wire fractures were found to invariably occur at the so-called neutral axis (in terms of the simple beam bending theory). The time interval between the first and the final wire failures in the flexural case indicated that regular inspection may provide some safeguard against sudden failure under fluctuating stress conditions. The design implications of the results of Hobbs and Ghavami [12] in relation to stays for guyed masts and suspension bridge hangers, were discussed by Hobbs and Smith [13] who proposed a tentative design procedure against bending fatigue failure. Raoof and Hobbs [5] proposed a theoretical model to try and explain the interesting and, at the same time, perhaps surprising experimental observations of Hobbs and Ghavami [12] in their bending fatigue tests that initial wire fractures invariably occurred at the neutral axis. The proposed model enabled one to predict the free-bending behaviour of a spiral strand, both within the zone of influence of a termination, and also in the free-field— i.e. well away from any termination effects. Their model was developed for a constant curvature imposed on an axially preloaded spiral strand fixed at one end. These authors accounted for both the geometrical and material non-linearities with the individual helical wires remaining linearly elastic and the interwire friction causing the material non-linearities. Raoof [14] compared the predictions of this theoretical model with some large scale experimental results which provided a fundamental insight into the, perhaps, initially puzzling experimental observations of Hobbs and Ghavami [12]. The conclusion drawn was that the primary mode of failure was interwire fretting fatigue between the often counter-laid wires in the vicinity of the partially restrained termination, which was greatest at the neutral axis, and least at the so-called extreme fibre position. Various predictions of this theoretical model were further validated by Raoof [14,15], who reported results based on large scale experiments on two 7.9 m long spiral strands with diameters of 39 and 41 mm. Numerous strain gauges were placed at the mouth of the socket on both strands (thirty on the 39 mm strand and twenty four on the 41 mm strand, with one electrical resistance strain gauge placed on each individual galvanised outer wire).

Raoof and his associates, in a series of publications as given in Ref. [6] further developed and manipulated their Orthotropic Sheet bending model (for the free-field behaviour) to try and reasonably understand the bending phenomenon away from the end terminations. Amongst a number of findings, Raoof and Huang [16] suggested a method for

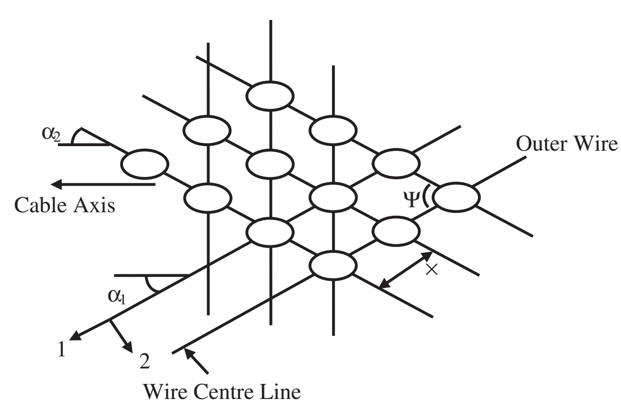

Fig. 2. Pattern of interlayer trellis contact patches.