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Finite element analysis of the fatigue strength of copper power conductors exposed to tension and bending loads

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ABSTRACT

The paper presents FE analyses for predicting longitudinal stresses from tension–tension and tension–bending fatigue tests of a 95 mm^2 stranded copper power conductor. As fatigue test results indicated that the fatigue performance was dominated by longitudinal stresses, the models were formulated by a combination of elastic beam and elastic–plastic beam-contact elements that included the friction. Two contact conditions were investigated: the point (trellis) contact between adjacent layers and the inline contact within each layer and between centre wire and inner layer. Due to the plastic deformations of the wires obtained from the manufacturing procedure, a simplified description of the contact behaviour was adopted and calibrated by axial tension testing. The FE models were further validated by calibration testing and mesh sensitivity checks. The simulated stresses were applied to attempt bridging the gap between the SN data obtained from full cross-section tension–tension and tension–bending testing and SN data obtained from individual wires testing.

1. Introduction

Floating vessels like ships and semisubmersibles are extensively used for production of oil and gas from offshore fields. Also offshore wind turbine concepts based on floating units have been developed. Electrical power cables are used in conjunction with floating units for provision of energy to installations on the sea bed, power from land to the floater, or export of power from a wind turbine to land. Power cables that are linked to a floating unit are subjected to fatigue loading from the waves and due to the movement of the vessel in the waves. Therefore, fatigue strength needs to be verified for design.

A power cable consists in general of multiple conductors each representing an assembly of individual wires usually made of copper or aluminium. Fig. 1a shows a typical offshore power cable for an alternating current (AC) three-phase system. One cable usually has three conductors, one for each phase. Each conductor consists of copper wires helically wound in layers around a centre wire.

During operation, a cable will be exposed to gravity, environmental loading from the sea, and to forces due to movements of the vessel. The gravity will induce a mean global tension ($\overline{T}$) and mean global torque moment ($\overline{M}_T$). The forces due to movements of the vessel induce a dynamic tensile load (ΔT) and torque (ΔM_T) (due to heave and surge motion) and dynamic curvatures ($\Delta\beta$) (from pitch and roll motion) acting on the cables. The most heavily loaded section is close to the attachment point (at section A–A) to the vessel (Fig. 2). Mean and dynamic tension will be transferred to the wires as tension and shear forces while the dynamic bending moment will induce local bending as well as axial friction forces into each individual wire.

As shown in Fig. 1b, the mean axial force ($\overline{F}_x$) in each wire is a function of the mean global tension ($\overline{T}$) and the mean global torque moment ($\overline{M}_T$). The dynamic axial force (ΔF_x) in each wire is a function of these, the corresponding dynamic quantities ΔT and ΔM_T, the dynamic curvature ($\Delta\beta$) and the coefficient of friction (μ) between the contact surfaces. The dynamic curvature results in local bending in each wire where ΔM_x is the dynamic torque moment about the helix tangential x-direction, ΔM_y is the dynamic bending moment about the helix bi-normal y-direction and ΔM_z is the dynamic bending moment about principal normal vector of the helix curve.

The wires in a stranded conductor are stranded helically in layers which leads to contact longitudinally both within and between each layer, which is illustrated in Fig. 3b. Contact within a layer and between centre and first layer is denoted inline contact. The global axial force will result in both longitudinal and transverse forces within the layer where the transverse forces will cause diameter reduction in the inline (hoop) direction of each wire. If cylindrical bodies with diameter D_1 and D_2 are pressed together with a certain load per unit length, p, a small continuous contact surface area will occur as shown in Fig. 4.

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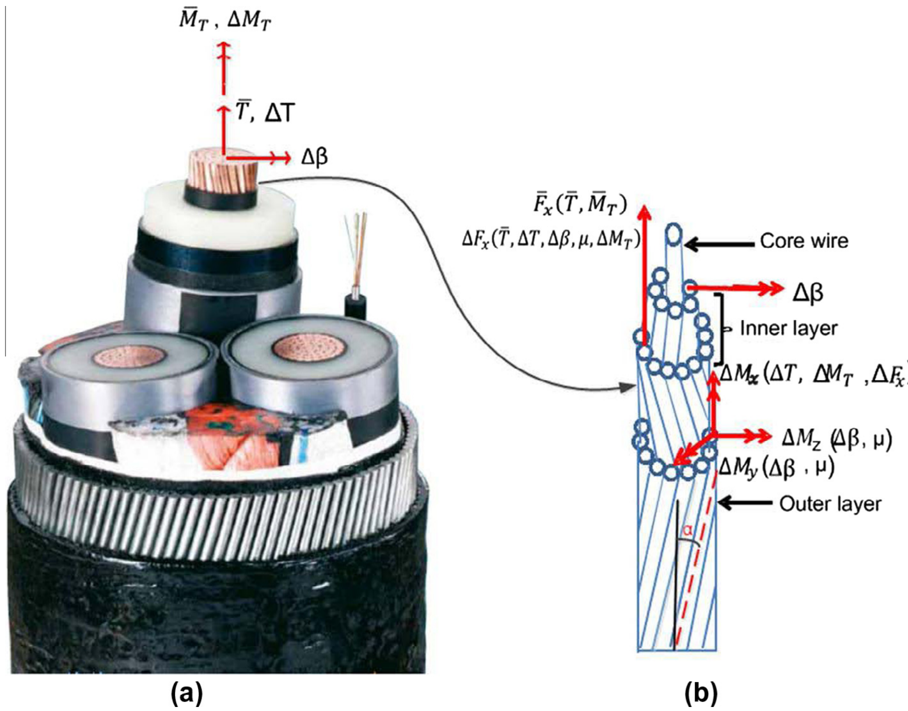

Fig. 1. (a) Offshore power cable for three-phase AC system using helically stranded copper conductor inside. (b) Helically stranded copper conductor with lay angle α exposed to dynamic and static loads.

Contact between wires in different layers is called point contact (Figs. 3a and 5).

A comprehensive literature study has been conducted with respect to models for describing fatigue and contact stresses in cabled structures. Mindlin [1] described the contact surfaces of two isotropic bodies subjected to normal and tangential loading without friction. Dong and Steidel [2] studied the contact stress conditions between layers of strands using a photoelastic technique. Hobbs and Raoof [3] have reported fatigue test results for socketed structural strands. They concluded that the fatigue behaviour was governed by several failure mechanisms related to the contact conditions close to the socket. Johnson [4] described the Hertzian contact stresses between two solid bodies under a certain normal load. A theory of contact was developed for predicting the shape of the contact area and the growth in size with increasing load; the magnitude and distribution of surface tractions, normal and possibly tangential forces, transmitted across the interface. Raoof and Hobbs [5] proposed an analytical model for relevant multi-layered stranded structures for determining the point and inline contact forces and associated relative displacements with its ends fixed against rotation. Raoof [6] developed from first principles a theoretical model using axial single wire data for predicting the axial fatigue of the full cross-section at constant load amplitude, and was able to correlate the theoretical predictions to observations from experimental testing. Raoof [7] concluded that his theoretical model provides useful upper bounds to the fatigue life of cables failing at the end termination and that the termination type significantly affects the observed fatigue life. Raoof and Huang [8] proposed simple methods for estimating strand plane section bending stiffness when imposed to cyclic bending and external hydrostatic pressures.

As opposed to the aforementioned authors, the present study focus on copper conductors applied in dynamic cables where the design is based on using protective steel armours and bending stiffeners to resist the external forces, thus limiting the tensile forces and curvatures in the copper conductor.

Zhou et al. [9] studied the plastic flow, local wear and fretting failure for overhead electrical conductors imposed by bending fatigue loads. Papailiou [10] presented a new model of conductors under simultaneous tensile and bending loads. During the bending loads, the model takes into account the interlayer friction and slip in the conductor. A mesoscale model has been developed by Hong et al. [11] in order to describe the bending behaviour of helically wrapped cable under tension. The model accounts for the nonlinear behaviour of the cable due to friction forces. Karlsen [12] simulated the fatigue mechanism in dynamic power cables by dynamic testing in tension and bending. He concluded that the effect of fretting on the fatigue properties was less dominant for copper conductors than for steel wires and ropes. However, there is no detailed information regarding the failure positions on the specimens. Lévesque et al. [13] presented investigations related to fretting fatigue of an overhead electrical conductor focusing on the contact conditions at the trellis contact points.

The copper power conductor investigated here further produced by a compacting procedure where the following features were noted:

1. Introduction of irregularities in wire geometries, specially for the outer layer due to irregular supporting point contact conditions.
2. An increase in the contact area, thus reducing the contact stresses.

The effect of irregularities on the fatigue performance of individual wires were investigated by Nasution et al. [14–16] where a FE model was presented that allowed transforming the nominal SN data into SN data of actual longitudinal stresses that included the effect of irregularities. Full cross-section SN data obtained from fatigue tension–bending tests results were also presented using a simple analytical stress model. Significant deviations were noted between the full cross-section SN data and the individual wire data which were believed to be due to: