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Interwire wear and its influence on contact behavior of wire rope strand subjected to cyclic bending load

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A B S T R A C T

The present study establishes a solving model for analyzing the interwire wear evolution of a wire rope strand subjected to cyclic bending load, in which the frictional contact and sliding between the wires are considered simultaneously. A wear experiment between the wires is conducted to study the wear behavior of the wires. Meanwhile, the proposed model is verified experimentally. Then the interwire wear and its effect on the contact behavior of the strand are analyzed. The results show that the interwire wear only happens on the side further from the curvature center of the bended strand than its neutral layer, and no wear happens when the wires are apart from each other or the interwire slippage is zero. As the wear process goes on, the wear region extends only along the normal direction of the core-wire contact line, and the maximum wear depth occurs at the middle position between the neutral layer and the furthest location from the curvature center. The contact pressure is distributed uniformly along the normal direction of contact line, but a significant stress concentration and local deformation happen at the position furthest from the curvature center of the bended strand.

1. Introduction

A wire rope is widely used in building, bridge, shipping, port and mining industries due to its high strength, good flexibility, impact resistance, stable operation and noiselessness. The wire rope is frequently loaded by tension, torsion and bending load in applications, which unavoidably results in contact and friction between the wires. Axial load and bending load in a simple straight wire rope strand bring about interwire pivoting and interwire sliding, respectively [1]. The interwire friction usually has little influence on the capability of the wire rope strand which is under the axial load, but its effect on the wire rope twisted around a sheave or drum cannot be ignored [2]. Particularly in periodic bending load conditions, long-time interwire friction and reciprocating slippage contribute to wire wear, which results in stress concentration and further the fracture of the wire rope. Therefore, it is of a great significance to conduct an in-depth study on the interwire wear mechanism to improve the design of wire ropes.

In the past years, some studies have been conducted on the friction and wear of wire ropes, most of which were conducted experimentally. For example, Rigde et al. [3] measured the strain of the wire rope caused by a periodic bending load. And their work shows that the strain amplitude has an important influence on the fatigue of the rope. A series of experiments conducted by Harris et al. [4,5] on interwire frictional wear show that there exists a linear relation between the abrasion loss and contact load, that abrasion-caused damage is found at contact zone edge, and that wear and bending stress of the wire rope leads to crack occurrence and ultimately causes the fracture failure. To avoid this failure, the lubrication on the wire rope was also studied. The experiment on wear performance of a wire rope from McColl et al. [6] in different lubricating conditions shows that both oil lubrication and grease lubrication effectively reduce the friction coefficient of the wire rope, especially under the lubrication condition with additive graphite. Zhang et al. [7] reported experimentally that there exists an inverse ratio between the fatigue life, wearing depth, wearing-in period and load, and that an increased contact load induced three-body wear. Cruzado et al. [8,9] measured the wear volume of steel wires with a profilometer at different contact loads, wear distances and contact angles. And they concluded that the friction coefficient of the wire rises as the contact load and wear reciprocating distance increase, while the contact pressure and wear resistance decline as the wire intersection angle decreases under a certain contact load. Studies by Xu et al. [10] on the wear of the wire rope shows that acid medium can augment the interwire slip and the wear scar depth in this condition compared with dry friction environment. Further, Wang et al. [11–13] assessed the wear of steel wires in different lubrication conditions.

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Nomenclature

A_c	Contact region between central and outside wires
$\bar{A}_2$	Cross-sectional area of deformed outside wire
E^*	Reduced Young's modulus
E_1^*, E_2^*	Composite Young's moduli of central and outside wires
e_x, e_y, e_z	Cartesian coordinates
G, G'	Components of bending moment on outside wire's cross-section
G_u^p	Green's functions of normal pressure for elastic deformation
G_u^s	Green's functions of shear stress for elastic deformation
H	Twist moment on outside wire's cross-section about z axis
h_c	Core-wire contact clearance
h_i	Initial clearance between central and outside wires
h_w	Wear depth
h_{w0}	Total wear depth of central and outside wires at core-wire contact line
I_c	Influence coefficient of contact pressure for elastic deformation
i_n	Number of nominal wear cycles
K, K', Θ	Components of external moments per unit length of outside wire centerline
k_l	Length ratio of nominal contact line and outsider wire centerline at deformed state
k_w	Coefficient of wear
L_s	Relative sliding distance between central and outside wires
l	Projection length of outside wire centerline
l_p	Initial lay length of wire rope strand
$\bar{l}_p$	Lay length of deformed strand
l_s	Length of outside wire centerline
N, N'	Components of shearing force on outside wire's cross-section
N_w	Total wear cycle
p	Contact pressure
R_1, R_2	Initial radii of central and outside wires
$\bar{R}_1$, $\bar{R}_2$	Final radii of central and outside wires in deformed state
$\bar{R}_{1y_c}$, $\bar{R}_{2y_c}$	Radii of surface curvature of central and outside wires along y_c direction
r_{h2}	Helical radius of outside wire centerline
$\bar{r}_{h2}$	Helical radius of deformed outside wire centerline
$\bar{r}_{hc}$	Helical radius of deformed nominal contact line
S	Accumulated sliding distance
T	Tensile force along z direction
u	Total deformation of core-wire contact
u_1, u_2	Deformations of central and outside wires along y_c direction
W_p	Total planimetric wear of central and outside wires
X, Y, Z	Components of external line load per unit length of outside wire centerline
X_c, Y_c, Z_c	Line loads per unit length of core-wire contact line
x, y, z	Normal, binormal and tangential directions at an point on outside wire centerline
y_c, z_c	Tangential and normal directions of core-wire contact line
α_2	Helical angle of undeformed outside wire
$\bar{\alpha}_2$	Helical angle of deformed outside wire
$\bar{\alpha}_c$	Helical angle of nominal core-wire contact line
ΔN_w	Number of wear cycles per nominal wear cycle
δ	Total contact deformation due to core-wire contact
δ_1, δ_2	Contact deformations of central and outside wires
κ	Bending curvature
κ_2, κ'_2, τ_2	Components of curvature and twist of outside wire centerline before deformation
$\bar{\kappa}_2$, $\bar{\kappa}'_2$, $\bar{\tau}_2$	Components of curvature and twist of outside wire centerline after deformation
μ_e	Equivalent shear modulus
ν	Poisson's ratio of wires
ξ_1, ξ_2	Tensile strains of central and outside wires
ϕ	Angle position of outside wire centerline relative to strand axis

In addition, numerical approaches have been used in some studies to simulate the wear evolution of the wire rope. Warburton and Bradford [14] presented a method to compute the volumes of the intersections of worn cylinders, according to the geometrical parameter of the wear scars. Based on the experimentally obtained coefficients of friction and wear, McColl et al. [15] realized a numerical solution of wear by combining of the modified Archard's wear model with a finite element software. They conducted the solution through a progressive loading way and also put forward an optimization method in decreasing computing time. Cruzado et al. [16–18] analyzed the wear of wires at different intersection angles by using a finite element method and wear model, and verified the numerical results experimentally. Johansson [19] studied the evolution of contact pressure in frictional wear process, and found that the contact pressure changes as the volumetric wear increases. And the work by Argatov et al. [20] shows that the influence of the contact pressure on the wear coefficient should be considered. Argatov and Tato [21] made a comparison between sliding wear solution obtained by an asymptotic model and that obtained by finite element method. Wang et al. [22] estimated the fatigue life of a steel wire and found that the structural location and material property of the wire exert a significant influence on its stress distribution and fatigue life in the finite element analysis of fretting wear evolution of the wire. Wang et al. [23] studied the crack initiation in a wear simulation of wire and found that the crack is liable to be found at the trailing edge.

Studies on the tribological performance of wire rope have been made so far, most of which were conducted experimentally. However, experimental studies are time-consuming and costly. And the local performances, such as the interwire contact pressure and deformation, are difficult to be obtained by experiments. As to the reported numerical works about wear of the wire rope, the interwire contact is usually studied through simplified point contact dealings. This is not completely in accordance with the real contact situation of wires in the wire rope, such as the helical line contact between the central and outside wires in a wire strand. Additionally, there are only few theoretical researches about the interior frictional wear of the cyclically bended wire rope, but the simultaneous consideration of the behaviors of bending, interwire contact and wear has not been conducted in these researches. To accurately evaluate the rope performances, the above bending, interwire contact and wear under the helical wire contact should be studied, which is helpful to improve the service performance of the wire rope.

With the consideration of factors including interwire friction, contact and wear, the present study establishes a solution model of frictional wear for a wire rope strand subjected to a cyclic bending load based upon the thin rods theory, elastic contact