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PREDICTIVE MODELING OF FRETTING-INDUCED FATIGUE FAILURE IN STEEL WIRE ROPES

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ABSTRACT
Steel wire ropes used in hoisting, crane, and mooring applications are conventionally qualified through time-consuming fatigue reliability tests. These tests do not separate the contribution of bulk fatigue from fretting wear caused by relative sliding and contact stress between stranded wires, which is the dominant damage mechanism in service. This paper presents a damage-based predictive model that combines bulk fatigue, represented through residual Young's modulus degradation, with fretting wear, represented through a stress-based damage evolution law governed by the shear stress range at the wire-to-wire contact. The model was implemented as a user material (UMAT) subroutine in Abaqus and calibrated against published fretting test data, giving a fretting wear damage coefficient of cf = 0.10 and a critical damage value of Dc = 0.90 for material removal. A fatigue fracture criterion based on the total dissipated energy (Edc = 32–34 J) was established and applied to a 1×7 steel wire rope, predicting a fatigue life of 820,000 cycles that is consistent in order of magnitude with industrial reliability test results.

KEYWORD
Steel wire rope, fretting wear, damage mechanics, fatigue life prediction, finite element analysis

INTRODUCTION
Steel wire ropes are widely used in hoisting and hauling applications, ranging from crane and elevator cables to mooring lines for floating production storage and offloading (FPSO) systems. Before a newly designed wire rope is approved for production, a sample must pass a reliability test in which it is subjected to tension-tension fatigue loading until failure. This test is time-consuming and requires a large collection of stress-life data to cover the many possible wire rope designs and stress ratios. A predictive tool that can assess the reliability of a wire rope design before it is physically tested would considerably shorten the product development cycle, as illustrated in Figure 1.

Conventional fatigue life prediction for wire ropes relies on the S-N curve together with mean-stress corrections such as the Goodman, Gerber or Soderberg diagrams. These phenomenological approaches are based on the average load over the net cross-sectional area of the rope and do not account for the failure of individual wires within a strand. More importantly, they do not capture the fretting wear that develops at the contact between stranded wires due to the winding-induced contact pressure and the relative sliding produced by axial straining under cyclic load. In high-cycle fatigue, fretting wear rather than crack initiation is the dominant damage mechanism in a wire rope: the contact surface is progressively scraped away until the remaining cross-section can no longer sustain the load, leading to a sudden fracture rather than a slowly propagating crack. The objective of this work is to develop and validate a damage-based model that combines bulk fatigue and fretting wear, and to demonstrate its use in predicting the fatigue life of a newly designed steel wire rope through finite element (FE) analysis.

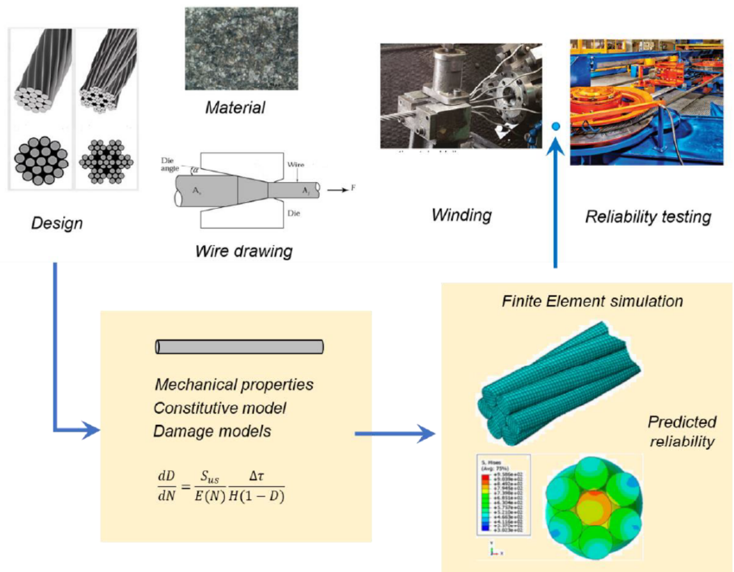

Figure 1: Preproduction activities of steel wire ropes.

MATERIAL AND METHODOLOGY

The fretting wear damage at the wire-to-wire contact is quantified using a scalar damage variable, D, that evolves from D = 0 (undamaged) toward a critical value, Dc, at which the material is considered removed. Following a continuum damage mechanics formulation (Chaboche & Lesne, 2007), the damage evolution rate is expressed in terms of the absolute maximum shear stress range, Δτ, experienced at the contact, the adhesive shear strength of the contact pair, Sus, the localized hardness, H(N), and the residual Young's modulus, E(N):

$$\frac{dD}{dN} = c\frac{S_{us}}{E(N)}\frac{\Delta\tau}{H(N)\cdot(1-D)}$$

where c is a calibration coefficient that reflects the surface condition of the contact pair, bulk fatigue entering through the degradation of E(N) and fretting wear entering through Δτ. The tensile, fatigue, hardness and sliding-wear properties of the drawn high-carbon steel wire needed to evaluate these terms were obtained experimentally and are reported in detail in Kamarudin et al. (2023); they are not repeated here.

The damage model was implemented as a user material (UMAT) subroutine in Abaqus/CAE, in which the damage variable degrades the elastic (Lamé) constants of the material at every integration point, and the stress, modulus and damage are updated after each load cycle. A load-cycle block method, with each block representing 10,000 cycles, was used to reduce computational cost. Two FE models were used: (i) a cross-wire contact pair model, with crossing angles of 45°, 60° and 90°, used to calibrate and validate the wear and fracture criteria against fretting test data reported by Llavori et al. (2019, 2021); and (ii) a 1×7 wire rope model (15.9 mm nominal diameter) representing the most critical contact plane within one pitch length, used to predict the fatigue life of the wire rope under a tension-tension fatigue load of 55.8 kN (20% of the minimum breaking load) and a load ratio of R = 0.1.

RESULT AND DISCUSSION

The fretting wear damage model was calibrated by matching the FE-predicted wear depth of the cross-wire contact pair (90° crossing angle) with the experimental wear depth reported by Llavori et al. (2019) at N = 150,000 cycles. A fretting wear damage coefficient of c = 0.10 together with a critical damage value of Dc = 0.90 gave a predicted wear depth of 44 µm, close to the measured value of 45 ± 7 µm, and Dc = 0.90 was therefore adopted as the criterion for wear-induced material removal. The calibrated model was independently validated using a 45° crossing-angle contact pair: the predicted wear scar was wider but shallower than that of the 90° pair, consistent with the experimental trend, since a smaller crossing angle produces a line contact with a larger contact area and correspondingly lower local shear stress.

Because the wear scar depth at fracture differs between wires of different diameters, a geometry-independent fatigue fracture criterion was sought. A macro-crack is assumed to initiate once the wear depth reaches one-third of the wire diameter, consistent with the established acceptance criterion for broken wires in a rope. The total dissipated energy, Ed, accumulated from the friction force–relative displacement hysteresis loop, was evaluated at this critical wear depth for six contact-pair conditions covering mean stresses from 597 to 1500 MPa and crossing angles from 45° to 90°. Despite this wide range of testing conditions, as shown in Figure 2, the critical dissipated energy converged to a narrow band of Edc = 32–34 J, supporting its use as a fatigue fracture criterion that is independent of the testing condition. The fatigue life predicted using this criterion was comparable with the experimental fatigue life reported by Llavori et al. (2021), with a difference of about 16% for one of the contact pairs.

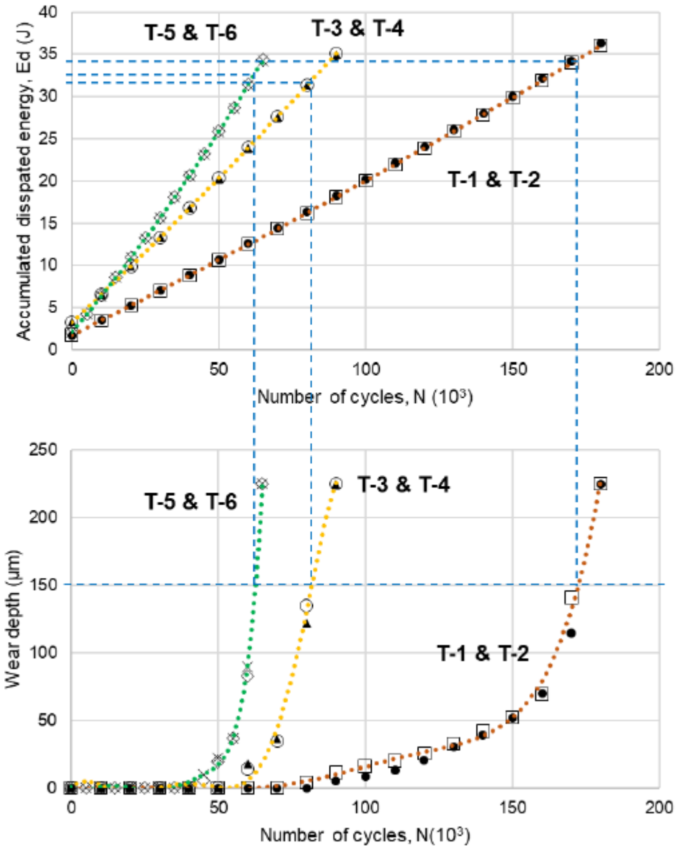

Figure 2: Wear depth evolution with an increasing number of cycles and the corresponding accumulated energy dissipation. Blue lines indicate critical wear depth and dissipated energy values

The calibrated model and the energy-based fracture criterion were then applied to the 1×7 wire rope model. The FE results showed that the core wire develops damage first, because it is shorter than the helically wound strands within one pitch length and therefore experiences greater axial straining under the same applied load. Within the critical plane, two contact zones govern the fretting wear of the core wire, so fatigue fracture is expected once the accumulated dissipated energy reaches half of the single-contact criterion, i.e., Edc/2 ≈ 16–17 J. This value was reached at N = 820,000 cycles, which was taken as the predicted fatigue life of the 1×7 wire rope at the simulated load level.

This predicted life is lower than, but of the same order of magnitude as, the fatigue life of 900,000 to 2,000,000 cycles obtained from reliability tests on the same wire rope configuration conducted by the wire manufacturer. The discrepancy is attributed mainly to two factors. First, the manufacturer's test used a higher maximum load (70% of the minimum breaking load, against 20% simulated here) and a higher load ratio (R = 0.8, against R = 0.1), both of which raise the applied stress range. Second, the tested wire rope was zinc-coated, whereas the FE model used the properties of bare (non-galvanized) wire; galvanization is reported to increase the fretting fatigue limit of contact wires by up to 1.7 times because the softer zinc layer enlarges the contact area and lowers the friction coefficient and contact stress (Dieng et al., 2007). Considering both factors, the prediction is a reasonable, conservative estimate suitable for screening newly designed configurations before they are committed to physical reliability testing.

CONCLUSION

A damage-based predictive model that combines bulk fatigue, through residual modulus degradation, and fretting wear, through a stress-based damage evolution law, has been implemented in a finite element framework using a UMAT subroutine in Abaqus. The model was calibrated and validated against published fretting wear and fretting fatigue data for cross-wire contact, giving a fretting wear damage coefficient of c = 0.10, a material removal criterion of Dc = 0.90, and a fatigue fracture criterion based on a critical dissipated energy of Edc = 32–34 J. Applied to a 1×7 steel wire rope, the model predicted a fatigue life of 820,000 cycles, consistent in order of magnitude with industrial reliability test data once differences in the applied load level and wire surface condition are accounted for. The approach offers a practical means of assessing the reliability of newly designed wire rope configurations before they are committed to costly and time-consuming physical fatigue testing. Future work should extend the model to account for crack propagation after wear-induced fracture initiation and for the effect of zinc galvanization on the contact and wear behaviour.

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