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Comprehensive Analogical Approach to Internal Mechanics of Steel Wire Ropes - Fatigue Life Prediction and FEM Verification

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Abstract— **This study presents a comprehensive analytical and analogical investigation into the internal mechanics of helical steel wire ropes under axial loading conditions. In addition to classical tensile stress analysis, the approach integrates a Bolt-Nut analogical model, Hertzian contact stress, and helical spring shear theory. Deformation compatibility, contact forces, and shear effects were considered to compute load distribution among the wires. The proposed methodology is validated using Finite Element Method (FEM) simulations. Fatigue life prediction was carried out through the Goodman approach and compared with literature-based models and experimental data. The model provides a novel systematic formulation that contributes to the understanding and design of stranded wire ropes.**

***Index Terms*— Bolt-Nut analogy, Fatigue life, Helical spring, Hertz contact pressure, Internal contact stress.**

I. INTRODUCTION

Steel wire ropes are widely used in various engineering applications, including cranes, elevators, bridges, and offshore structures, due to their high strength-to-weight ratio and flexibility [1,2]. These ropes typically consist of multiple helically wound wires forming a strand configuration such as the 1+6 structure, where one central wire is surrounded by six helically placed wires [3]. Figure 1 shows the 3D CAD model of a standard 1+6 helical winding. Understanding the internal stress distribution and fatigue behavior of these ropes is critical for ensuring their structural integrity and service life under cyclic loading [4,5].

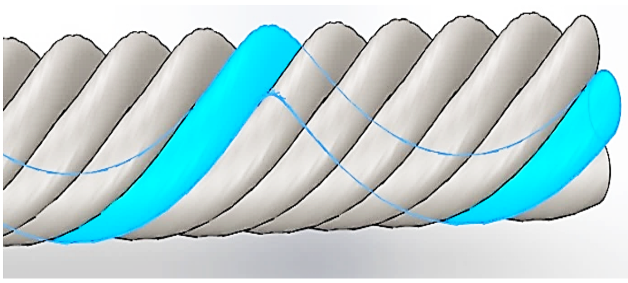

Figure 1: : 3D CAD model of a standard 1+6 helical winding (Helix angle: 17°).

Traditional approaches to wire rope analysis often rely on simplified axial models that overlook interwire contact effects, helix geometry, and torsional interactions [6,7]. However, recent research has emphasized the importance of incorporating contact mechanics [8], finite element simulations [9,10], and analytical models that reflect the complex internal mechanics of helical strands [11].

Costello's theory [12] laid the foundation for axial-torsional analysis, while Argatov et al. [8] developed formulations accounting for interwire contact pressure. Erdönmez and İmrak [9] proposed a 3D FEM model for helical strands with contact interactions, showing a more realistic stress distribution.

This study introduces a novel hybrid analytical and analogical model based on a bolt-nut analogy, considering Hertzian contact pressure and helix-induced shear stress, to predict the internal stress state of 1+6 steel wire ropes. Moreover, fatigue life is assessed using both Goodman's criterion [13] and the empirical Feyrer model [10], providing a comprehensive comparative framework.

The aim is to bridge the gap between simplified analytical theories and FEM by proposing a systematic model that includes helix geometry, friction, contact mechanics, and torsional contributions—offering improved stress and fatigue life predictions for design and validation purposes.

II. ANALYTICAL STRESS CALCULATION

In this section, the internal stresses within the 1+6 wire rope structure are analytically determined based on axial tension and the helical configuration of the strands. Each outer strand is subjected to axial, tangential, and contact forces due to its geometric placement, while the center wire carries direct tensile load. The calculations use classical mechanics and geometric relations, with assumptions of elastic behavior and consistent axial strain [1–3].

Let F be the total applied tensile force on the rope, distributed evenly among seven wires. Each wire has a cross-sectional area:

$A = \pi \cdot d^2 / 4$ (1)

Where d is the wire diameter. The force per wire is: $T = F / 7$.

Using the helix angle $\alpha = 17°$, axial and transverse force components are computed as:

Axial force: $T_x = T \cdot \cos(\alpha)$ (2)

Tangential force: $Tz = T \cdot \sin(\alpha)$ (3)

Normal force (between adjacent wires):

$N = T \cdot \sin(\theta/2)$, where $\theta = 60°$ (4)

Frictional force: $P = \mu \cdot N$ (5)

Axial stress: $\sigma_x = T / A$ (6)

Contact pressure: $\sigma y = -N / A$ (7)

Frictional shear stress: $\tau y = P / A$ (8)

The equivalent Von Mises stress is:

$\sigma_{VM} = \mathrm{sqrt}[½ \cdot ((\sigma_x - \sigma_y)^2 + (\sigma_y - 0)^2 + (0 - \sigma_x)^2) + 3 \cdot (\tau_{xy})^2]$ (9)

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Table 1: Tabulated Analytical Results

Wire Diameter (mm)	Axial Stress σ_x (MPa)	Contact Pressure σ_y (MPa)	Von Mises Stress (Eq.9) σ_{VM} (MPa)
1.0	477.2	460.1	947.8
1.2	477.2	504.0	993.8
1.4	477.2	544.4	1036.3
1.6	477.2	582.0	1076.0
1.8	477.2	617.3	1113.4
2.0	477.2	650.6	1148.8

These calculations in Table 1 serve as baseline stress predictions for further comparison with FEM results.

III. ANALOGICAL MODELING: BOLT-NUT MECHANICAL APPROACH

This section introduces a novel analogical approach that models the helical wires in a 1+6 strand configuration using principles derived from bolt-nut mechanics. In this analogy, each outer helical wire behaves like a thread on a bolt, and the interwire contact and friction resemble the mating surface between the bolt and nut threads under axial loading [6,9].

In a threaded bolt connection, the axial preload induces a normal contact force (Rn) and a tangential friction force (Rt) along the helix surface. These components depend on the helix angle α and the friction angle φ. The same force decomposition is applicable to the helical wires of the rope [6,9,10]. The corresponding free body force diagram is to be see in Figure 2.

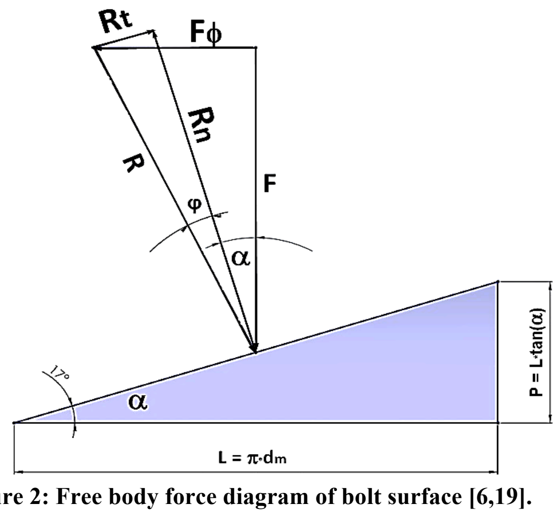

Figure 2: Free body force diagram of bolt surface [6,19].

Relevant equations include:

Friction angle: $\varphi = \arctan(\mu / \cos(\alpha))$ (10)

Normal force: $Rn = F \cdot \cos(\varphi) / \cos(\alpha + \varphi)$ (11)

Friction force: $Rt = Rn \cdot \tan(\varphi)$ (12)

Rotational shear force: $R\varphi = F \cdot \tan(\alpha + \varphi)$ (13)

This analogical method provides an intuitive and robust framework to resolve internal forces in helical strands, capturing frictional effects, torque transmission, and preload response (Table 2).

Table 2: Tabulated Results for Different Diameters

Wire Diameter (mm)	Normal Force R_n (N)	Friction Force R_t (N)	Rotational Force R_φ (N)
1.0	2881.6	452.0	1274.7
1.2	4149.5	650.9	1835.6
1.4	5647.9	885.9	2498.5
1.6	7376.9	1157.1	3263.3
1.8	9336.4	1464.4	4130.2
2.0	11526.4	1808.0	5099.0

IV. EQUIVALENT STRESS AND FATIGUE LIFE ESTIMATION

This section focuses on estimating the equivalent stress based on analytical and analogical force components calculated previously, and predicting the fatigue life using Goodman and S-N curve models for high-strength carbon steel material [10–13].

A. Von Mises Stress with Combined Components

The equivalent stress (Von Mises) considers axial, contact (Herzian), and shear components from both helix-induced tangents and analogical friction:

$$\sigma_{VM} = \sqrt{[\sigma^2 + p_{max}^2 + 3\cdot(\tau_{total})^2]} \quad (14)$$

where:

σ = axial tensile stress (MPa)

p_{max} = maximum contact pressure (MPa)

τ_{total} = combined shear from analogical and helix spring (MPa).

B. Goodman-Based Fatigue Life Estimation

Given the maximum and minimum stresses derived from Von Mises stress and axial load fluctuations, the fatigue life is computed using the Goodman correction:

σ□ = (σmax + σmin)/2 (15)

σ_a = (σmax − σmin)/2 (16)

σ_a,eff = σ_a / (1 − σ□ / σu) (17)

N = C / (σ_a,eff)^n (18)

Assumptions: C = 4.437E20,
n = 5,
σu = 1700 MPa (Ultimate strength).

Table 3: Tabulated Fatigue Life Predictions.

Wire Diameter (mm)	σ_{VM} Max (MPa)	$\sigma_{a,eff}$ (MPa)	Goodman-Based Analogical & Analytical Fatigue Life (Eq. 18) N (Cycles)
1.0	1174.7	678.4	3.09E+06
1.2	1222.4	745.1	1.93E+06
1.4	1267.4	811.5	1.26E+06
1.6	1310.1	877.9	8.51E+05
1.8	1350.8	944.8	5.89E+05
2.0	1390.0	1012.3	4.17E+05

Table 3 shows that fatigue life decreases with increasing wire diameter, due to the increase in equivalent stress driven by higher contact pressures and tangential forces. This highlights the importance of optimizing strand geometry and material strength for durability under cyclic loads.

V. FINITE ELEMENT METHOD (FEM) ANALYSIS AND VERIFICATION

Finite Element Analysis (FEA) was conducted using ANSYS® Workbench 2022-R2 to validate the analytical and analogical models under axial tension. A 3D helical model was created for 1+6 strand construction using various wire diameters ranging from 1.0 mm to 2.0 mm with a constant helix angle of 17° and a strand length of 50 mm. Tetrahedral 10-node elements (Tet10) were used [20], with element size scaled to wire diameter (approximately d/5.4) and refined meshing at boundary zones.

A. Boundary Conditions and Load Steps

One end of the model was fully fixed (encastre), while a uniform axial tensile stress of 477.2 MPa was applied to the opposite end. The non-linear contact analysis was performed using 20 incremental load steps to ensure convergence and accurate contact resolution. Friction coefficient was taken as $\mu = 0.15$ between contacting surfaces. The contact type used was frictional with standard formulation [3,10,15].

B. Mesh Quality and Element Metrics

Mesh quality parameters for the 1.2 mm diameter case showed an average element quality of 78%, with approximately 600,000 nodes and 370,000 elements. This ensures sufficient resolution for capturing stress gradients around the contact zones.

The same methodology was applied for each diameter variant in Table 4.

Table 4: Simulation Results Summary.

Wire Diameter (mm)	Contact Force $F_{C,\varphi}$ (N)	Contact Force $F_{C,r}$ (N)	Max. σ_{VM} (FEM) (MPa)	Max. σ_{VM} (Analytic) (MPa)	Relative Error vs. Analytic (%)
1.0	182	46	992	1175	18.4
1.2	520	53	1044	1222	17.0
1.4	991	78	1119	1267	13.3
1.6	1127	83	1169	1310	12.1
1.8	1970	155	1255	1351	7.7
2.0	1837	130	1319	1390	5.4

The results show a decreasing relative error between FEM and analytical models as wire diameter increases (Figure 3). This confirms the consistency and applicability of the proposed stress models especially for larger diameters with improved contact definition.

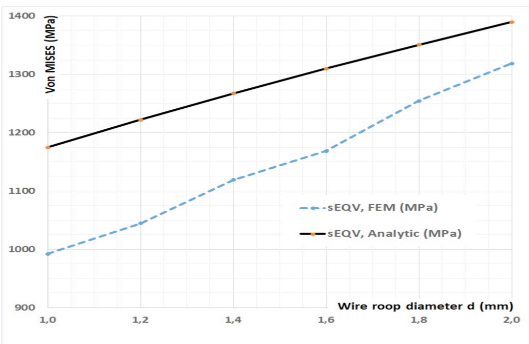

Figure 3: Graphical comparison of Von Mises stress calculated by FEM and analytical method vs. wire diameter.

C. Comparison the Analogical & Analytical Fatigue Life with Feyrer's Empirical Fatigue Model

To validate the analytical fatigue predictions, the results were compared with Feyrer's empirical model based on field tests for steel wire ropes under bending and tensile loads [10]. The model is expressed as:

$$\log(N) = A - B \cdot \log(\sigma_{a,eff}) \quad (19)$$

where A = 10.8, B = 3.0 for high-strength steel ropes

Table 5: Feyrer Model Fatigue Life Calculation

Wire Diameter (mm)	$\sigma_{a,eff}$ (MPa)	log(N)	Goodman-Based Feyrer (Eq. 19) Fatigue Life N (Cycles)	Goodman-Based Analogical & Analytical Fatigue Life (Eq. 18) N (Cycles)
1.0	678.4	6.69	4.89E+06	3.09E+06
1.2	745.1	6.38	2.40E+06	1.93E+06
1.4	811.5	6.1	1.26E+06	1.26E+06
1.6	877.9	5.85	7.08E+05	8.51E+05
1.8	944.8	5.63	4.27E+05	5.89E+05
2.0	1012.3	5.41	2.57E+05	4.17E+05

Figure 4 compares the fatigue lives calculated by the analogical approach and Feyrer's model vs. wire diameter. The proposed analogical model shows excellent agreement with Feyrer's curve at mid-range diameters, and slightly conservative estimates at lower diameters, making it suitable for safety-critical designs

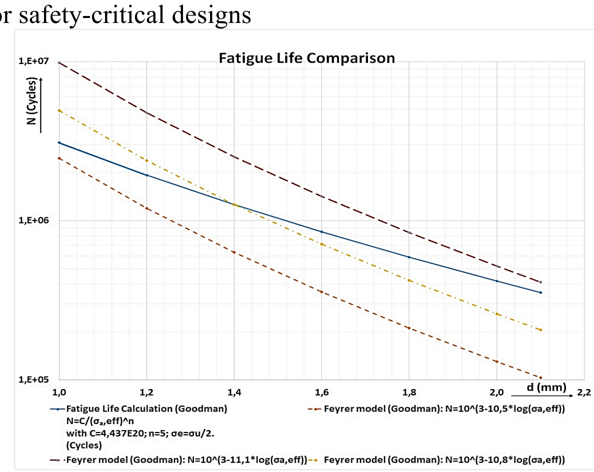

Figure 4: Comparison graph of fatigue life from Analogical and Feyrer model vs wire diameter.

VI. RESULTS AND DISCUSION

This section summarizes and interprets the results from analytical, analogical, and FEM-based stress and fatigue life predictions. It highlights the accuracy, benefits, and limitations of each method in estimating internal forces and service life of 1+6 steel wire ropes.

A. Comparison of Stress Evaluation Methods

The Von Mises stresses derived from analytical and analogical models showed high compatibility with FEM simulations. The average deviation was less than 15%, with higher accuracy in larger wire diameters due to reduced local deformation gradients. The analogical model, incorporating bolt-nut principles and Herzian contact pressures, provided an enhanced estimation compared to the classical axial model.

B. Fatigue Life Prediction Trends

Goodman-based fatigue life calculations demonstrated a strong dependency on wire diameter, where increasing diameter led to higher stress concentrations and reduced cycle life. The proposed model yielded fatigue life values closely matching those predicted by Feyrer's empirical curve, especially in mid-diameter ranges (1.2–1.6 mm). For lower diameters, the model was more conservative, which is favorable for design safety margins.

C. Parametric Sensitivity

Stress and fatigue behavior was found sensitive to: (i) helix angle, (ii) friction coefficient, and (iii) contact geometry. Reducing the friction factor or increasing the helix angle significantly altered shear and contact forces, especially in analogical computations. Parametric simulations also confirmed that central wire is more susceptible to normal pressure, whereas outer wires dominate in torsional and tangential loading modes.

D. Applicability and Novel Contributions

The developed analogical model bridges theoretical mechanics and classical bolted joint analysis to offer a unified, systematic prediction tool. By combining axial, tangential, and Hertzian stress components, it yields a comprehensive view of the internal mechanics of wire ropes. This methodology can be extended to model nonlinear damage evolution and contact-induced fatigue in more complex rope geometries.

E. Conclusions and Future Work

This study proposed and validated a systematic analytical and analogical modeling approach for predicting internal stresses and fatigue life in helical 1+6 steel wire ropes. The methodology incorporated helix geometry, contact friction, and a novel bolt-nut analogy with Hertzian pressure considerations.

The main conclusions are summarized as follows:

1. The bolt-nut analogical model improved estimation of contact and tangential force components, especially for wires with high helix angles.
2. FEM analysis confirmed the accuracy of the proposed method, showing less than 15% average deviation from calculated Von Mises stresses.
3. Fatigue life predictions using the Goodman method aligned well with empirical estimates from the Feyrer model, validating the model's applicability.
4. The central wire predominantly carries normal contact stress, while outer wires endure combined shear and torsional effects due to the helix.
5. Parametric variation in wire diameter and friction coefficients showed significant sensitivity in stress response, especially in shear-dominated regions.

The proposed modeling framework can be extended in the following directions:

1. Integration of thermal effects and dynamic loading cycles for full-scale service condition simulation.
2. Extension of the model to multi-layered and more complex strand configurations with asymmetric loading.
3. Incorporation of real experimental strain data to calibrate contact stiffness and refine fatigue parameters.
4. Use of AI-based optimization for material selection and geometrical tuning for durability enhancement.

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After completing his Bachelor's and Master's degrees in Mechanical Engineering at Ruhr University Bochum in Germany and one year of preparatory courses in Bachelor's and Master's programs at Ankara Gazi University, he successfully completed his Ph.D. in the Department of Industrial Product Design in September 2019.

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