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*M. KARUSKEVYCH, O. KARUSKEVYCH, V. KORCHUK, I. LOZOVSKIY**State university "Kyiv aviation institute», Kyiv, Ukraine***ROTATING BENDING FATIGUE TEST MACHINE**

Steel wire ropes are widely employed across numerous industries, particularly in aviation, where they are used in onboard cranes, winches, hoists, mechanical control systems, and cargo-securing tie-down assemblies. The mechanical performance of steel wire ropes is governed by the properties of their individual components. Steel wire is a primary structural element of these ropes. In service, wire ropes are exposed to cyclic operational loading during cargo lifting, movement, and handling, as well as additional dynamic loads caused by acceleration. In many cases, they also operate in unfavorable and aggressive environments. Together, these factors lead to fatigue, wear, and corrosion, critically influencing the service life and reliability of wire ropes. This study presents the development of a compact rotating-bending fatigue testing machine specifically designed to evaluate the fatigue behavior of steel wires. The base configuration is intended for laboratory testing at dry air; however, further upgrades will enable testing in aggressive corrosive media, various surfactants, greases, and corrosion-preventive compounds to investigate adsorption-induced weakening phenomena, including the Rebinder effect. Analytical stress calculations based on Reuleaux's classical approach were validated by finite element modeling, demonstrating close agreement between the methods. The developed machine provides an efficient and reliable tool for studying fatigue mechanisms in steel wire materials under realistic operating conditions.

Key words: *rotating bending fatigue test; steel wire; wire rope; fatigue behaviour; finite element analysis; surfactant environment; Rebinder effect; cyclic loading; corrosion-fatigue interaction; laboratory testing machine*

Introduction. Steel wire ropes are widely used across many fields, including aviation. In particular, winches and hoists on cargo aircraft rely on wire ropes as essential components. During service, wire ropes are subjected to wear, corrosion, and fatigue. The primary modes of fatigue in wire ropes include tension–tension fatigue, bending-over-sheave fatigue, free-bending fatigue, and torsional fatigue. A combination of degradation mechanisms—such as simultaneous fatigue and corrosion—produces a cumulative and particularly hazardous effect.

The complex interaction of mechanical loading and environmental exposure creates significant challenges for predicting rope service life and assessing accumulated damage. Therefore, experimental investigation of rope degradation processes remains highly relevant.

Steel wire ropes (Fig. 1) [1] have a complex hierarchical structure. The smallest structural element is the individual wire, which may be manufactured from various metallic materials. Steel wires are produced in multiple grades that differ in strength, wear resistance, fatigue performance, corrosion resistance, and bending characteristics. Wires are helically arranged and twisted into strands, which in turn form the rope. The rope core supports the strands and maintains their relative position

under tensile and bending loads. Cores may be made of natural fibers, synthetic fibers, or steel.

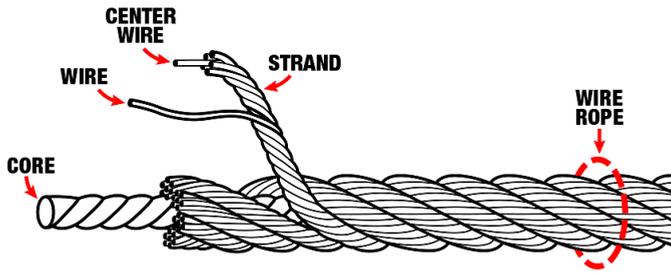


Fig.1- Steel wire rope structure [1]

Steel wire ropes operate for many years under varying mechanical loading conditions and environmental influences. High reliability requirements for lifting and hoisting equipment continue to stimulate research into wire-rope behavior under repeated loading. Excessive bending, twisting, stretching, or vibration results in the accumulation of fatigue damage and ultimately wire fractures.

The internal stress–strain state of wire ropes is complex. Their helical, multi-component construction provides multiple load-carrying paths and, in effect, a fail-safe design with a high degree of redundancy [2]. The helical geometry also induces radial load components under axial tension. These radial forces produce normal contact stresses between adjacent wires, generating surface shear and enabling broken wires to gradually recover their load-sharing capability along the rope length.

Fatigue behavior of wire ropes has been extensively investigated. It has been shown [3] that rope diameter, mean stress, socket type, lay angle, and rope length significantly influence fatigue life. Small-diameter ropes behave differently than large-diameter ones: their S–N curves are more sensitive to stress-range changes, and their fatigue resistance at 2×10^6 cycles is generally higher. Typically, fatigue tests are stopped before complete rope failure. However, the chosen termination criterion—such as the first wire break, failure of 5% of wires, or total rope fracture—strongly affects the measured fatigue resistance.

In [4], results of bending-fatigue tests and damage monitoring of steel wire ropes were reported. Damage was evaluated by counting broken wires, and an attempt was made to predict rope endurance based on the first two wire breaks. Another study [5] demonstrated that contact stresses between strands lead to fatigue-prone wear zones. The influence of pulley material was examined in [6]; wire ropes operating over nylon pulleys exhibited approximately twice the bending-fatigue life compared with ropes used with cast-steel pulleys.

Corrosive environments are well known to degrade steel ropes [7]. Moisture penetrates the rope structure, causing not only external corrosion but also internal attack of individual wires. In addition to corrosion, certain liquids belonging to surfactants can influence the plastic-deformation behavior of metals [8]. According to the Rebinder effect [9], surface-active species adsorbed on the metal surface decrease

surface energy, facilitating slip-band formation and promoting material weakening under stress.

Understanding wire-robe performance under the combined action of cyclic loading and environmental effects requires a step-by-step approach, beginning with the study of individual wire behavior and failure mechanisms. Numerous testing devices have been developed for this purpose. In the present work, a new compact fatigue-testing machine for steel wires is introduced and described.

Compact rotating bending fatigue test machine.

The objective of the design was to develop an inexpensive, compact, and reliable machine capable of testing wires at maximum cyclic stress levels corresponding to the expected in-service stresses experienced by steel-rope wires. The proposed machine satisfies the requirements of [10]. Rotating-bending fatigue testing of small-diameter solid round wire is achieved by looping a specimen of predetermined length through an arc of 90° to 180°. The resulting bending stress is defined by the geometry of the formed loop.

This test method is intended for evaluating wire fatigue behavior within the linear-elastic strain (stress) regime. However, the obtained results have certain limitations due to the radial strain gradient inherent in bending. At the same time, this stress distribution is advantageous for investigating surface-related effects, such as adsorption phenomena caused by surface-active agents.

A simplified schematic of the developed machine is presented in Fig. 2.

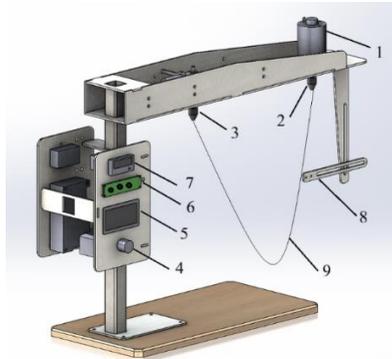


Fig.2. Scheme of the new rotating bending machines for wires testing

In the fig.2: 1 – spindle drive (electric motor); 2 – driving spindle; 3 – driven spindle; 4 – rotational speed regulator; 5 – rotational speed display; 6 – control panel; 7 – cycles counter; 8 – guides; 9 – specimen (test wire).

Wire stress calculations

Stress in the wire at the bending can be found by simple formula proposed by Reuleaux in 1865 [11]. He took each wire of the rope as a simple beam in flexure and by combination of the formula:

$$M = SI/C$$

and

$$M = EI/R$$

found that the stress in the extreme fiber due to bending was:

$$S = Ed/D,$$

where E – modulus of elasticity;

d – diameter of a single wire;

D – the diameter of the Drum in the Reuleaux formula or diameter of the loop of the wire in test machine;

C – constant depending on the number of wires in the strand.

General requirements for the steel wire ropes are described in the standards, for example [12]. For many machines in aviation the two lay steel rope type TK construction 6 x19 (1+6+12) + 1 x19 (1+6+12) shown in the fig.3 is used.

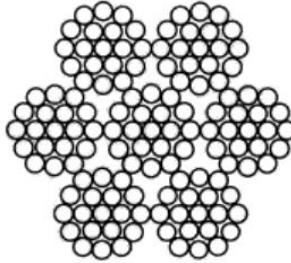


Fig.3. Steel rope 6 x19 (1+6+12) + 1 x19 (1+6+12)

Let us consider the loading capabilities of cold-drawn non-alloy steel wire for ropes, manufactured from steel with a modulus of elasticity $E = 199 \text{ GPa} = 199\,000 \text{ MPa}$ [13]. Tensile strength grades are shown in table 1[14]. Coating made by zinc or Zn/Al alloy.

The endurance limit of cold-drawn non-alloy steel wire for ropes is in the range of **40% to 50% of its ultimate tensile strength**. Loading regimes must provide stresses above the fatigue limit.

Table 1

Tensile strength grades and ranges of nominal diameters [14]

Tensile grade strength, MPa	Range of nominal diameters, mm	
	Bright and coated – Class B	Coated – Class A
	Class B	Zinc or Zn/Al Class A
1180	0.2 to 1.80	-
1370	0.2 to 7.00	0.70 to 7.00
1570	0.2 to 7.00	0.70 to 7.00
1770	0.2 to 6.00	0.70 to 6.20
1960	0.2 to 5.00	0.70 to 4.20

2160	0.2 to 4.00	-
2260	0.2 to 3.40	-
2360	0.2 to 2.70	-

For example, if the ultimate tensile strength of the steel wire is approximately 1600 MPa (a common value for high-strength wires), its endurance limit would be in the range of **640 to 800 MPa**.

Stresses for set of fatigue test regimes were calculated (table 2).

Table 2

Stress regimes range for current design

Diameter of the loop of the wire in test machine, D, mm	100	150	200	250	300
Diameter of a single wire, d, mm	0,5	0,5	0,5	0,5	0,5
d/D	0,005	0,00333	0,0025	0,002	0,00166
Maximum stress in wire, MPa (Conventional calculations)	995.0	662.67	497.5	398	330.34
Maximum stress in wire, MPa (FEM calculations)	983,09	655,64	492,1	393,91	323,78
Difference between Conventional and FEM calculations, %	1,2	1,1	1,1	1,0	2,0

The diameter of the wire specimens is taken as 0.5 mm. For loop diameters in the range of 100 to 300 mm, the maximum stresses calculated using the formula are within the range of 330 to 995 MPa.

Table 2 presents the geometric characteristics of the loading scheme and the corresponding calculated results for the maximum stresses in the loading cycle.

Results of the Finite Elements Analysis are shown in the fig.4.

Comparison of the results of the stress in wire under the rotating bending calculated by the Reuleaux formula and found with application of Finite Element Analysis are presented in the table 2.

As it is seen from the table 2, diameters of the wire loop less than 150 mm provide the loading condition that lead to the failure of the wire specimen due to the fatigue.

The results obtained using the conventional analytical method and those from the finite-element stress-strain analysis demonstrate good agreement.

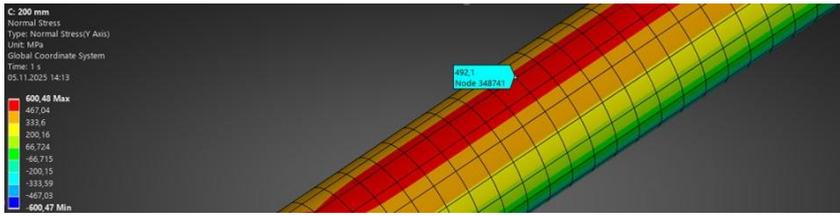


Fig. 4. Results of the Finite Element Analysis of the wire loaded at the process of test - distribution of the stress in the wire cross section

Testing in the liquids surrounding

The motivation for studying the influence of various liquids on the fatigue behavior of wire ropes stems from the assumption that many of these substances possess surface-active properties, classifying them as surfactants. Surfactants can affect deformation-induced damage in the surface layer of metals through the mechanism known as the Rebinder effect [15]. This effect, first identified by Rebinder in 1928 and subsequently confirmed by numerous researchers, is not a form of corrosion. Instead, the adsorption of surface-active species facilitates deformation and fracture by lowering the surface energy of the metal, thereby promoting localized plastic shear. In many cases, adsorption-driven weakening may exceed the effects of purely chemical interactions.

Despite decades of study, the influence of surfactants on metal fatigue remains insufficiently understood. Considering the stringent reliability and durability requirements for aircraft systems, this phenomenon must be taken into account when evaluating the long-term performance of steel wire ropes.

The newly developed testing machine enables systematic investigation of the effects of a wide range of surfactants, including corrosion-preventive compounds (CPCs), lubricating greases, oils, and operating fluids of aviation systems. According to long-standing practice dating back to the 1950s, the influence of surface-active agents can be benchmarked against that of oleic acid.

Oleic acid (cis-9-octadecenoic acid $\text{CH}_3(\text{CH}_2)_7\text{CH}=\text{CH}(\text{CH}_2)_7\text{COOH}$) is monounsaturated fatty acids. It is a colorless viscous liquid with melting point $t_{\text{melt}} = 13,4^\circ\text{C}$ for the unstable beta version and $t_{\text{melt}} = 16,3^\circ\text{C}$ for a stable alpha-modification, and boiling point $t_{\text{boil}} = 286^\circ\text{C}$. Oleic acid is a traditional surfactant in the study of the Rebinder effect [15].

Upgrading of the machine to make it able to conduct fatigue tests at the condition of the surfactants can be made simply by the installation of the bath with investigated liquid in such a way that the most loaded part of the wire goes through the liquid.

Conclusions

The fatigue damage of wire ropes is determined by the behavior of their individual components, namely the single wires. Testing single wires allows the identification of fundamental patterns in fatigue performance. For obtaining preliminary information on the resistance of steel wires to cyclic loading, rotating-bending tests are considered a reliable and straightforward method.

A new testing machine for fatigue evaluation of steel wires has been designed and manufactured. The capability to achieve the required stress levels was confirmed analytically, while finite element analysis verified the accuracy of stress calculations obtained by conventional methods. The machine can also be upgraded to perform tests on wire specimens in liquid environments, including exposure to surfactants.

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УСТАНОВКА ДЛЯ ВИПРОБУВАНЬ НА ВТОМУ ПРИ ОБЕРТОВОМУ ЗГІНІ

В авіації сталеві канати використовуються у бортових кранах, лебідках, підйомниках, системах механічного керування та вантажно-кріпильних пристроях. Механічні характеристики сталевих канатів визначаються властивостями їх складових елементів. Сталевий дріт є основною структурною одиницею канатів. Під час експлуатації канати зазнають циклічного навантаження при підйомі, переміщенні та обробці вантажів, а також додаткових динамічних навантажень, спричинених прискореннями. У багатьох випадках вони працюють в несприятливих і агресивних середовищах. Сукупність зовнішніх факторів призводить до втоми, зношування та корозії, що істотно впливає на строк служби та надійність канатів. У роботі представлено розробку компактної машини для випробувань на втому при обертовому згині, призначеної для дослідження втомної поведінки сталевих дротів. Базовий варіант установки передбачений для лабораторних випробувань в середовищі повітря, проте подальша модернізація забезпечить можливість тестування зразків у агресивних корозійних середовищах, різних поверхнево-активних речовинах, мастилах і антикорозійних сполуках для вивчення адсорбційно-індукованого послаблення металу, зокрема ефекту Ребіндера. Аналітичні розрахунки напружень в дроті, виконані на основі класичного підходу були підтверджені методом скінчених елементів, що показало високу відповідність результатів. Розроблена машина забезпечує ефективний і надійний засіб дослідження механізмів втоми сталевих дровових матеріалів в умовах, наближених до реальних експлуатаційних.

Ключові слова: випробування на втому міцність при обертовому згині, сталевий дріт, сталевий канат, втомне пошкодження, метод скінчених елементів, поверхнево-активне середовище, ефект Ребіндера, циклічне навантаження, випробувальна машина.

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