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A REVIEW OF MACHINES FOR WIRE ROPES FATIGUE TEST

Review of the test machines designed to assess characteristics of steel wire ropes covers analysis of the equipment for fatigue tension-tension tests, torsion tests, sheave bending tests. Variety of the test machines concepts is determined by the diversity of the operational factors influencing the wire ropes loading. The importance of the single wire tests for the understanding of steel wire ropes fatigue behavior in terms of the step-by-step study of the wire ropes damage mechanism study is shown. Necessity to account for effects caused by contact interactions between the wires, as well as between ropes and environment is shown.

Key words: *wire ropes, fatigue test, test machines, tension-tension, torsion, sheave bending, damage.*

Introduction. Steel wire ropes are used in many applications. High requirements to their safety define attention to the fatigue strength, reliability, life span, resistance to the corrosion, inspectability.

Steel wire ropes origin from the more strong lifting machines components, namely chains.

Wire ropes have a set of advantages: Less expensive than chain of an equivalent capacity; for a given capacity, wire rope is lighter with a smaller diameter; wire ropes are stronger than chains of equivalent size.

Unfortunately, wire ropes cannot easily be repaired, thus damaged wire ropes must be removed from service; they have lower versatility, for example, wire rope that is highly resistant to abrasion cannot endure bending fatigue as well as wire rope designed for fatigue resistance; wire ropes prone to abrasion, kinking, and crushing; wire rope should not be used in high-temperature or highly corrosive environments.

Mechanical properties of rope that need verification and testing include: Breaking force, Elongation, Fatigue lifetime, Fatigue strength, Torque strength.

To ensure safe application of wire ropes many relevant standards have been created. Examples of the standards for steel wire ropes are:

- ISO 2408:2017, Steel wire ropes – Requirements [1]. This standard specifies requirements for the manufacture, testing, acceptance, packing, marking and issuing the certificate of quantity of wire ropes. It is applicable to round strands ropes and compacted strand ropes made from wires ropes that are uncoated (bright), zink-coated or Zn-Al coated. It is not applicable to ropes for mining purposes, aircraft control, aerial ropeways and funiculars, and lifts.

- ASTM A931-18, Standard Test Method for Tension Testing of Wire Ropes and Strand [2]. This test method covers the tension testing of wire ropes and strand at room temperature, specifically to determine the measured breaking force, yield strength, elongation, and modulus of elasticity.

- ASTM A938 / ISO 7800 - Standard Test Method for Torsion Testing of Wire [3]. This method measures the simple torsion properties of metallic wire. This standard performs a single direction twist to failure on wire specimens that can span many different materials and geometries. These tests determine the number of rotations until failure as well as the peak torque.

- ASTM E2948-14 - Standard Test Method for Conducting Rotating Bending Fatigue Tests of Solid Round Fine Wire [4]. Rotating bending fatigue testing of small diameter solid round wire is possible by looping a specimen of predetermined length through an arc of 90° to 180°. The bending stress is determined from the geometry of the loop thusly formed. A constant temperature can be maintained by immersing the specimen in a constant temperature fluid bath or test media. This test method is intended to obtain the fatigue data in the fatigue regime where the stresses are predominately and nominally linear elastic**.** However, the stress, also, pre-strain, which can influence fatigue life, is not included in this test method.

Nowadays contemporary standards for wire rope tests cover probably almost all aspects of the wire rope design, application and test. Nevertheless, increasing application of wire ropes encourages design of new machines with specific functions.

Evolution of fatigue test machines and state of the art. The oldest information about ropes applications are dated from approximately 12000 to 9000 BC. Leonardo da Vinci in 16th century made two sketches of machines for the production of ropes. Between 1824 and 1838 the mining engineer Albert from Germany realized the advantage of the hemp rope; but he also saw the advantages of the higher tensile strength of the iron chain. His attempt to combine the advantages of these two hoisting means marks the origin of the wire rope [5]. Albert described the design of the first wire rope, the process of production and testing. Albert carried out the first bending fatigue tests of chains and wire ropes. Today these tests are considered to be the first fatigue tests ever performed on a scientific basis.

Contemporary wire ropes test principles are presented in fig. 1 [6].

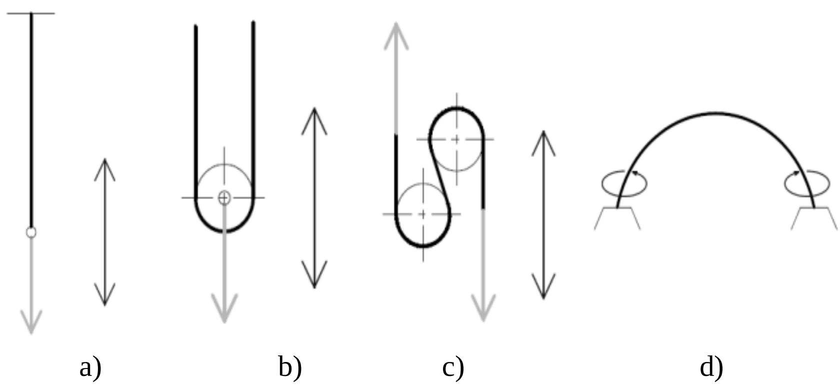

Fig.1. Wire rope fatigue test systems: a) tension; b) simple bending; c) reverse bending; d) rotary bending [6]

Many test machines include two stress regimes: tension-tension fatigue and bending over sheave (BoS) fatigue for steel wire ropes (fig.2) [7].

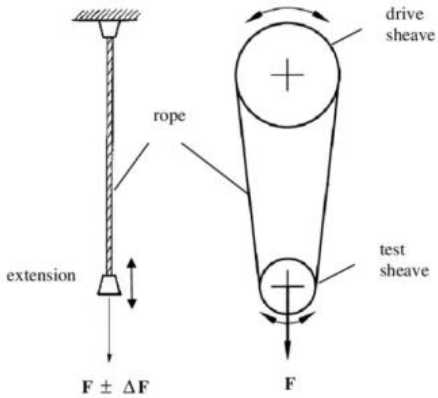

Fig.2. Principles of test machines: tension-tension fatigue (left) and bending over sheave fatigue (right) [7]

BoS fatigue test machine shown in the fig.3 comprises: Electric motor (3), drive sheave (1), test sheave (2). Constant tensile load, S, on the test sheave is produced by lever (5) and additional weights in order to simulate real working conditions.

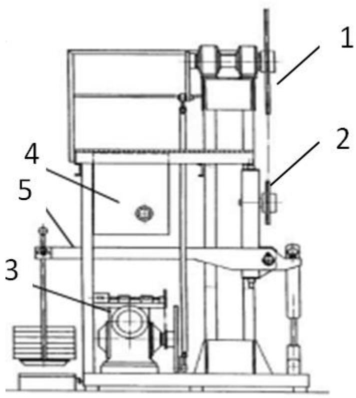

Fig.3. Bending fatigue test machine [7]

Scheme of the simplest conventional sheave bending machine, where a steel wire rope travels back and forth over a single test sheave is shown in fig.4 [8].

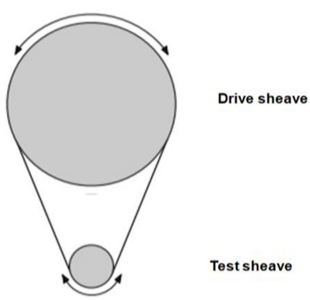

Fig. 4. Conventional bending fatigue machine [8]

In this design middle section of the rope subjected twice bigger number of the loading cycles than the rest of the rope (fig.5).

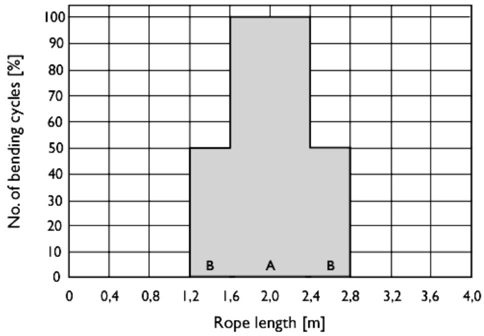

Fig.5. Bending cycle distribution in a conventional fatigue machine [8]

As it seen from fig. 5 the stroke of a conventional bending fatigue machine is relatively short, resulting in a very short test section A.

Fig. 6 also illustrates conventional bending fatigue machine. This machine has additional problem: the heat generated by bending the rope dissipates only via the sheaves.

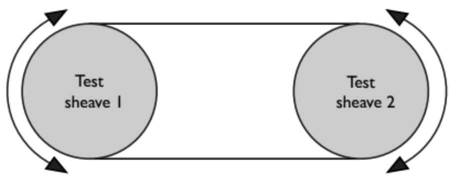

Fig.6. Conventional bending fatigue machine with two test sheaves and a closed rope loop [8]

Bending a fiber rope causes internal abrasion as the fibers rub against each other and an increase in rope temperature due to the effects of friction. As every fiber has a temperature threshold were the fiber properties decline, is it essential to take measures to ensure that the temperature limit is not reached. A typical test machine is shown in fig.7[9].

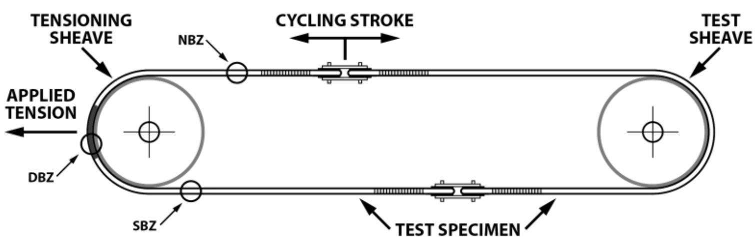

Fig.7. Two sheave test machine with a closed rope loop [9]

The sheaves are customized to the rope diameter and thus replicate the actual structure. Testing was used to determine the conditions that would result in a rope temperature increase up to the rope fiber's temperature limit. Temperature is measured in the Double Bend Zone (DBZ), in the Single Bend Zone (SBZ), in the None Bend Zone (NBZ) through the use of thermocouples inserted in the centre of the rope. Sheave and ambient temperature were also measured.

Bending over Sheave test machine with fluctuating tension load is shown in fig.8 [10].

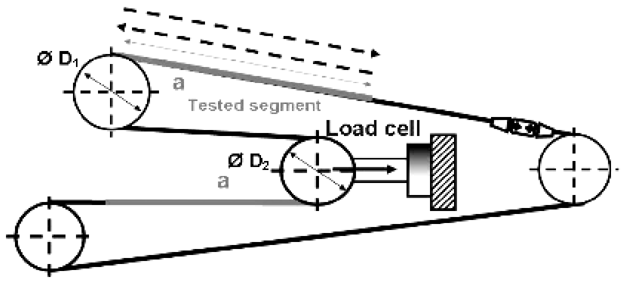

Fig.8. Bending over Sheave test machine with fluctuating tension [10]

By specific mechanism and controlling system this machine may provide the ability to test wire ropes under bending over sheaves with tension fluctuations at specific timing.

In the design shown below (fig.9) [11] the test rope is made into continuous loop by the use of the backing rope intended to avoid torque interaction. The test sheave is connected to a servohydraulic actuator controlled by the digital control system. This maintains a constant tension during testing. The length of the rope which runs on and off the test sheave each cycle is controlled by the crank connected to the drive sheave. Adjusting the angular position of the crescent-shaped plate alters the throw of the crank to set the bending motion.

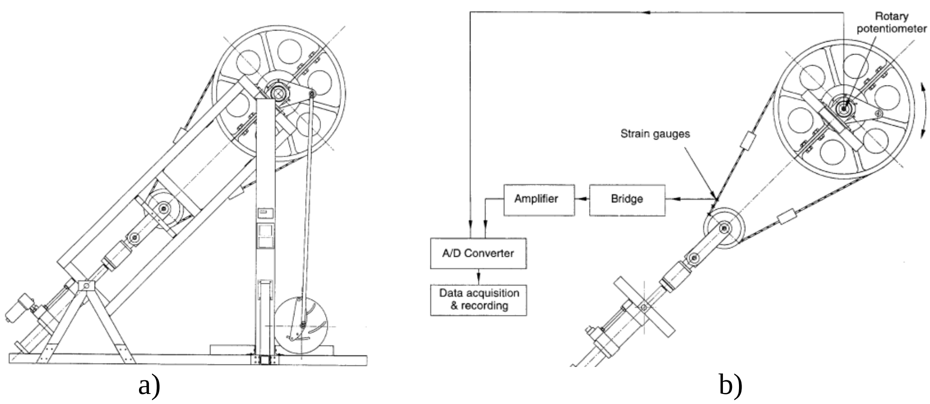

Fig.9. Bending over Sheave test machine with fluctuating tension: a) general view; b) strain measurement system [11]

The miniature strain gauges were attached to the outer 1.2 mm wires. Ten strain gauges were used on each test sample. Since the lubricant is used for rope, careful cleaning of the wire surface is required.

The machine described in the paper [12] designed to cause fatigue damage in varying degrees in a long sample of wire rope (fig.10). A range of degradations ranging from minimal damage to a condition of imminent failure. The “three-sheave” shortens the dimensions of the machine and multiplies the number of rope loading cycles. The machine is computer controlled.

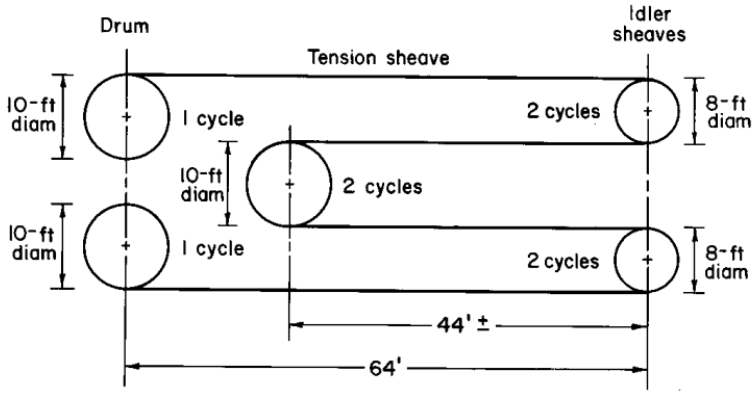

Fig.10. Rope path for “three-sheave” test machine [12]

In the work [13] rotary bending fatigue test machine has been described. In this machine a neutral spindle with the axle parallel to the motor spindle axle is added to simulate the rope bending on a pulley (fig.11). The preliminary calculation of the stress in the wire of the wire rope can be found by the formula proposed by Reuleaux in 1865 [14]. 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

$$S = Ed^1/D,$$

where E – modulus of elasticity;
d^1 – diameter of a single wire;
D – the diameter of the Drum (loop of the wire in test machine);
C – constant depending on the number of wires in the strand.

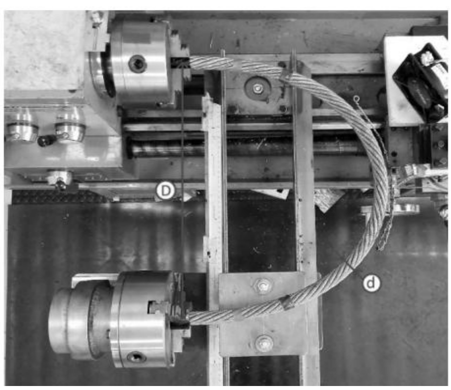

Fig.11. Rotating bending fatigue test machine [13]

The importance of single wire fatigue tests. The role of the single wire fatigue tests for the understanding the ropes behavior can be compared with the role of the single crystals study for understanding the nature of polycrystals damage.

The single wire behavior doesn't cover all aspects of the wire rope fatigue process, because wires of the rope work at the condition of the friction between the wires, contact stresses, wear, etc., but it is necessary for the understanding the mechanism of the wire damage itself.

In the simplest form machine for the wires fatigue loading (fig.12) can be designed according to the rotating bending concept [15].

Fig.12. Wire specimen in the spindles of rotary bending machine [15]

This kind of machines could be upgraded to consider important factors: environment, temperature, stresses parameters, etc. Example of the rotary bending fatigue test machine for single wire study is shown in fig.13 [16]. In this machine unlike many competitive machines, the wire is driven from both ends eliminating the possibility of induced torque in the wire. Range of speed available: 0 - 10,000 RPM. Optical Break Detector is capable of detecting a break of wire diameters ≥ 0.1 mm, in air or clear liquid. It can detect breaks in coated or other non-conductive wires.

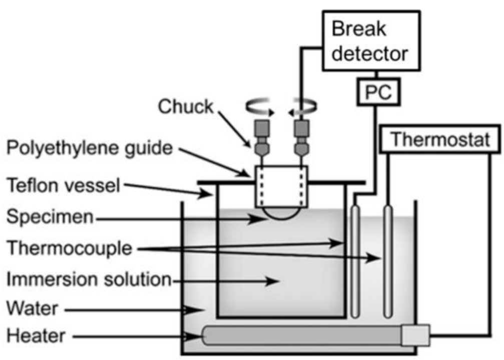

Fig.13. Rotary bending fatigue test machine for the study of environment effect [16]

One more design based on the same principle has been described in the paper [17]. The bench consists of two fixed supports and two supports constrained to have the same displacement (fig.14). The motor is connected to the wire by a special elastic joint and it is free to move to accommodate the deformation of the wire. The supports of the wire are free to rotate with respect to a vertical axis to follow the deformation of the wire. The two central supports are moved by a hydraulic actuator. The movement of the supports is guided by linear rails. By this arrangement, the displacements of the two central supports are constrained to be equal.

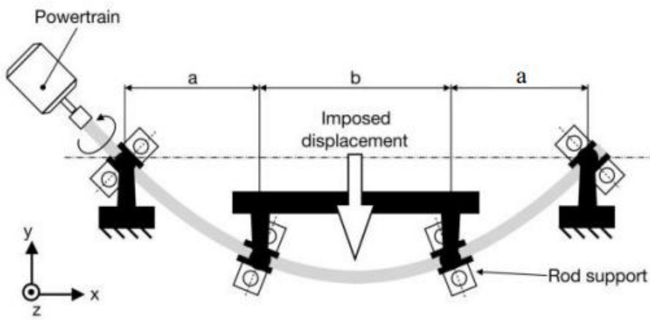

Fig.14. Four point rotary bending loading system [17]

Diagram of the bending moment acting on the wire when subjected to a four point bending loading scheme is shown in fig.15.

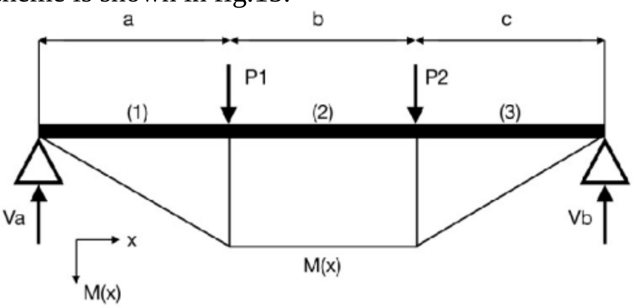

Fig.15. Four point rotary bending test: reaction forces and bending moment [17]

Middle part of the tested (2) represents the zone of the wire where a constant bending moment is acting.

In the analysis of wire ropes service life not only fatigue characteristics of the metal must be taken into account. The friction between the wire causes the wear stress concentrators and this provide cumulative damage effect.

Review of contemporary researches devoted to the problems of friction and wear of wire ropes components is presented in the work [18].

It is shown that fretting wear occurs under the action of different contact loads and contact stresses, resulting in stress concentration and even failure of the steel wire. To the moment the effects of different contact loads, crossover angles, displacement amplitudes, impact loads, longitudinal vibration of different frequencies and amplitudes, and the influence of temperature rise, low temperature, lubrication status, corrosion, etc., on the friction and wear characteristics of wire rope have been studied.

The role of the friction coefficient is considered in the paper [18]. The coefficient of friction has a direct effect on wear. It is shown also that the effect of friction coefficient on mechanical properties of the wire ropes can be studied with the aid of finite element simulation.

Based on the research results, the main factors affecting the fatigue life of steel wire ropes are: a) Manufacturing factors (wire material and its temper, surface treatment, twisting force, presence of lubricant, type of lubricant, etc.); structural factors (wire rope type, lay direction, lay distance, etc.); application factors (distance between sheaves, sheaves diameter, grooves of the sheaves geometry, ratio of the sheave diameter to the rope diameter, impact load, environment, elastic vibration, friction coefficient, etc.).

Taking into account the complex of affecting factors, the tests of wire ropes and their components, strands and wires, look as mandatory procedures to ensure long and reliable service life of the steel wire ropes.

Conclusion. Steel wire ropes have many applications. Variety of applications defines the wide spectrum of load conditions. Wire ropes work under the tension, bending, and torsion. Mechanical loading accompanied by the action of additional factors: aggressive environment, abnormal temperatures. Operational defects make the task of the wire rope technical state assessment very complex. Analytical methods are not able to assess consumed life of the ropes accurately. That is why experimental study of the wire ropes fatigue is a task of a great practical value. Existing test machines cover different loading conditions but special applications require unique approach for the design of test machines. Special attention must be drawn to the machines able to test single wires which are in fact basic building blocks of any wire ropes.

References

1. ISO 2408:2017, Steel wire ropes – Requirements. 16-06-2017.
2. ASTM A931-18, Standard Test Method for Tension Testing of Wire Ropes and Strand.
3. ASTM A938 / ISO 7800 - Standard Test Method for Torsion Testing of Wire.
4. ASTM E2948-14 - Standard Test Method for Conducting Rotating Bending Fatigue Tests of Solid Round Fine Wire.
5. Roland Verreet. A Short History of Wire Rope https://www.ropetechnology.com/downloads/brochures/bro_a-short-history-of-wire-rope.pdf
6. Mazurek P. (2023) A Comprehensive Review of Steel Wire Rope Degradation Mechanisms and Recent Damage Detection Methods//Sustainability, 15(6):5441; https://doi.org/10.3390/su15065441
7. Onur Y.A., Imrak C.E. (2011) The influence of rotation speed on the bending fatigue lifetime of steel wire ropes // Proceedings of the Institution of Mechanical Engineers Part C- Journal of Mechanical Engineering Science 225, 520–525. https://doi.org/10.1243/09544062JMES2275
8. Verreet R. et al. A new and innovative wire rope bending fatigue machine. https://www.ropetechnology.com/downloads/brochures/bro_a-new-and-innovative-wire-rope-bending-fatigue-machine.pdf
9. Lankhorst – the importance of keeping cool. https://www.lankhorstoffshore.com/about-us/news-events/cbos-the-importance-of-keeping-cool
10. Testing for drum winders mining, heavy duty cranes and large rope diameters. Matron Rope and Wire Rope Engineering. http://www.mre-rope.com/PAGE9.asp
11. Ridge Isabel M.L. (2000) Measurement of cyclic bending strains in steel wire rope//The Journal of Strain Analysis for Engineering Design. https://doi.org 10.1243/0309324001514288

12. Bartels J.R., McKewan W.M., Miscoe A.J. Bending Fatigue Tests 2 and 3 on 2-Inch 6x25 Fiber Core Wire Rope. Report of investigations 9429.
https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ri9429.pdf

13. Freddy P., Solazzi L., Donzella G. **(**2023) Prediction of rope bending fatigue life based on wire breaking rate// FME Transactions, VOL. 51, No 1, 59-70; https://doi.org/10.5937/fme2301059F

14. Coleman W.F., Rugg D.M. (1910) Stresses in wire ropes bent over sheaves, University of Illinois, 64 P.

15. Rotating Beam Wire Fatigue Tester Model FTX. https://nmds.co.jp/assets/pdf/blockwise/Wire%20Fatigue%20Tester.pdf

16. Fumiyoshi Yamashita *et al.* (2019) Effect of Nonmetallic Inclusions on Fatigue Properties of Superelastic Ti-Ni Fine Wire // Metals, 9, 999; https://doi.org/10.3390/met9090999

17. Ballo F., *et al.* (2019) Tempered Wire Fatigue Testing // SAE Technical Paper 2019-01-0532, https://doi.org/10.4271/2019-01-0532

18. Weihua Cui *et al.* (2021) Influence of friction coefficient on mechanical properties of braided wire rope in winding traction state //*J. Phys.: Conf. Ser.* 2076 012074. https://doi.org/10.1088/1742-6596/2076/1/012074

19. Peng Y., et al. (2023) Friction and wear of multiple steel wires in a wire rope //*Friction*, 11(5): 763-784. https://doi.org/10.1007/s40544-022-0665-y

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ОГЛЯД СУЧАСНИХ МАШИН ДЛЯ ВИПРОБУВАНЬ КАНАТІВ НА ВТОМУ

Огляд випробувальних машин розроблених для дослідження характеристик сталевих канатів містить аналіз обладнання для втомних випробувань «розтяг-розтяг», випробування на кручення, «вигин на шківу». Різноманіття концепцій випробувальних машин обумовлено різноманіттям факторів, які визначають умови навантажування канатів. Показана важливість випробувань одиничних дротів сталевих канатів відповідно до покрокового підходу до дослідження механізму пошкодження канатів в цілому. Показана необхідність урахування ефектів, обумовлених контактною взаємодією дротів канатів, а також взаємодією канатів і оточуючого середовища.

Ключові слова: дротові канати, втомні випробування, випробувальні машини, розтяг-розтяг, кручення,згин на шківу, пошкодження.

Список літератури

1. ISO 2408:2017, Steel wire ropes – Requirements. 16-06-2017.
2. ASTM A931-18, Standard Test Method for Tension Testing of Wire Ropes and Strand.
3. ASTM A938 / ISO 7800 - Standard Test Method for Torsion Testing of Wire.
4. ASTM E2948-14 - Standard Test Method for Conducting Rotating Bending Fatigue Tests of Solid Round Fine Wire.
5. Verreet R. A Short History of Wire Rope https://www.ropetechnology.com/downloads/brochures/bro_a-short-history-of-wire-rope.pdf.
6. Mazurek P. A Comprehensive Review of Steel Wire Rope Degradation Mechanisms and Recent Damage Detection Methods//Sustainability, 2023. 15(6):5441; DOI: 10.3390/su15065441
7. Onur Y.A., Imrak C.E. The influence of rotation speed on the bending fatigue lifetime of steel wire ropes // Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science 225 2011, 520–525. DOI: 10.1243/09544062JMES2275
8. Verreet R. et al. A new and innovative wire rope bending fatigue machine. https://www.ropetechnology.com/downloads/brochures/bro_a-new-and-innovative-wire-rope-bending-fatigue-machine.pdf
9. Lankhorst – the importance of keeping cool. https://www.lankhorstoffshore.com/about-us/news-events/cbos-the-importance-of-keeping-cool
10. Testing for drum winders mining, heavy duty cranes and large rope diameters. Matron Rope and Wire Rope Engineering. http://www.mre-rope.com/PAGE9.asp
11. Ridge Isabel M.L. Measurement of cyclic bending strains in steel wire rope//The Journal of Strain Analysis for Engineering Design · November 2000, DOI: 10.1243/0309324001514288
12. Bartels J.R., McKewan W.M., Miscoe A.J. Bending Fatigue Tests 2 and 3 on 2-Inch 6x25 Fiber Core Wire Rope. Report of investigations 9429.
https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/ri9429.pdf

13. Freddy P., Solazzi L., Donzella G. Prediction of rope bending fatigue life based on wire breaking rate// FME Transactions, VOL. 51, No 1, 2023, 59-70; DOI: 10.5937/fme2301059F

14. Coleman W.F., Rugg D.M. Stresses in wire ropes bent over sheaves, University of Illinois, 1910, 64 P.

15. Rotating Beam Wire Fatigue Tester Model FTX. https://nmds.co.jp/assets/pdf/blockwise/Wire%20Fatigue%20Tester.pdf

16. Fumiyoshi Yamashita *et al.* Effect of Nonmetallic Inclusions on Fatigue Properties of Superelastic Ti-Ni Fine Wire // Metals 2019, 9, 999; doi:10.3390/met9090999

17. Ballo F., *et al.* Tempered Wire Fatigue Testing // SAE Technical Paper 2019-01-0532, 2019, https://doi.org/10.4271/2019-01-0532

18. Weihua Cui *et al.* Influence of friction coefficient on mechanical properties of braided wire rope in winding traction state //*J. Phys.: Conf. Ser.* 2021, 2076 012074. DOI 10.1088/1742-6596/2076/1/012074

19. Peng Y., et al. Friction and wear of multiple steel wires in a wire rope //*Friction*, 2023, 11(5): 763-784. https://doi.org/10.1007/s40544-022-0665-y

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