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# FATIGUE LIFE OF COMPACTED WIRE ROPES FOR APPLICATIONS IN DEEP MINING

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**Abstract:**
Recent months have highlighted the progressing energy crisis across Europe in connection with the severe sanctions imposed on the import of hydrocarbons and coal from Russia. This is particularly visible in Poland, where over 40% of electricity is generated from coal, while in individual households it is the primary source of heat. This situation puts the already enigmatic plans of shutting down coal mining in Poland into question. Therefore, work aimed at increasing the extraction capacity of existing shafts while maintaining the highest level of operational safety is still valid. This article concerns the issues of the fatigue life of compacted ropes used as hoist ropes in mine shafts. The discussion regarding the use of these ropes among shaft hoist users has been going on for several years. This paper presents the unique results of compacted rope fatigue tests carried out at the Central Mining Institute in Katowice. In the authors' view, these results and their interpretation should serve to clarify several important aspects that arouse the interest of users.

***Key words:*** *steel wire rope, fatigue tests, compacted ropes, fatigue durability*

## INTRODUCTION

The dangerous circumstances provoked by the war in Ukraine continue to manifest themselves in the end of 2022 year. The energy crisis progresses across Europe in connection with the severe sanctions imposed on the import of hydrocarbons and coal from Russia. This is particularly visible in Poland, where over 40% of electricity is generated from coal, while in individual households it is the primary source of heat. This situation puts the already enigmatic plans of shutting down coal mining in Poland into question. Therefore, work aimed at increasing the extraction capacity of existing shafts while maintaining the highest level of operational safety is still valid.

This article concerns the issues of the fatigue life of compacted ropes used as hoist ropes in mine shafts. The discussion regarding the use of these ropes among shaft hoist users in Poland has been going on for several years. It is obvious that ropes of this type fulfil the basic criteria determined by the relevant regulations for hoist ropes [1], but their price and the objective difficulties in assessing their condition using magnetic and visual methods lead to significant doubts [2, 3] and continue to spark discussions. This paper uses the unique results of compacted rope fatigue tests carried out at the Central Mining Institute in Katowice, Poland [4]. In the authors' view, these results and their interpretation should serve to clarify several important aspects that arouse the interest of users. The article presents the basic technologies for compacted strand production and the resulting performance and strength characteristics of such ropes [3, 4, 5]. The work ends with conclusions pertaining exclusively to the strength test results as well as a list of the most important literature references.

## LITERATURE REVIEW PRODUCTION OF ROPES FROM COMPACTED STRANDS – REVIEW

The production technology and structure of ropes known as "compacted ropes" has been known for dozens of years [3, 5], but in practice until recently they found only sporadic application, primarily in fishery and hoisting cranes with drum shafts. In mining, over the last twenty years these ropes were used in only several cases in Poland. One of the primary reasons for this situation is the lack of complex studies examining the influence of these ropes' new structure on their strength properties, reliability and life as well as the possibility of determining their condition during operation by means of common visual and magnetic methods. Monograph [3] stood out in this context, though it was only a study of individual cases of application. The basic characteristic distinguishing the structure of these ropes in relation to those commonly utilised (referred to henceforth as "conventional ropes") is the presence of area contacts between interacting wires in strands produced with linear wire contact. The fatigue limit for steel wire used in steel wire ropes is critical to determining their potential application [6]. Steel ropes have high reliability [7]. However, the fatigue of wire rope will cause unpredictable risk to life security [8]. Nowadays, the reliability analysis and life prediction are widely concerned [9, 10, 11, 12, 13].

Due to the additional production processes involved, steel ropes formed from compacted strands are more expensive than equivalent ropes with strands made with linear wire contact. As a result of plastic strain, strands produced from wires with linear contact achieve area contact between the deformed wires in subsequent layers. Such a structure is obtained primarily by introducing significant and cost-generating technological modifications during the strand production process. The process involves a number of technologies. In general, they consist in the mechanical compression of a strand with linear wire contact in the radial direction, which leads to its plastic deformation. Following the compacting process, the wires in the strand undergo permanent deformation. This results in a decreased diameter of the strand while retaining its metallic cross-section. The cross-section of the wires forming the strand changes from a round shape to that resembling a honeycomb, while the wires come into area contact. Two technologies for compacted strand production are presented in Fig. 1.

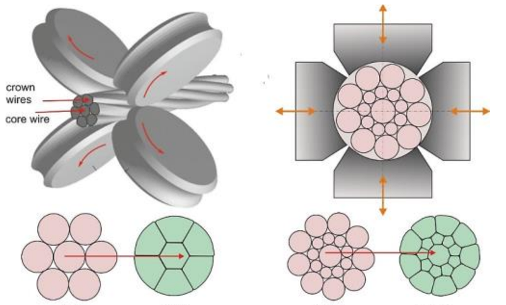

*Fig. 1 Compacting methods for strands with linear wire contact: top left – strand rolling, top right – swaging, bottom – compacting examples of 6x7 and 6x19S strands*
*Source: [4, 5].*

The obtained strand strain in any compacting method ranges within 6%÷30% and is defined by formula (1). The strain is calculated as the percentage area variation of a circle circumscribed about the strand as a result of compacting ($S_o$ [mm$^2$] – $S_k$ [mm$^2$]) relative to the variation that the area would undergo in the case of total strand compression ($S_o$ [mm$^2$] – $S_{\min}$ [mm$^2$]). As a result of compacting, the final strand diameter decreases even by over a dozen percent.

$$Z = \frac{S_0 - S_k}{S_0 - S_{\min}} \cdot 100\%, \quad (1)$$

where:

$S_o$ – area of a circle circumscribed about a strand [mm$^2$],
$S_k$ – strand cross-section after compacting [mm$^2$],
$S_{\min}$ – minimum strand cross-section that can be achieved after compacting until total strand compression [mm$^2$].

The greatest strain occurs in the external layer wires and gradually decreases in the deeper-placed wires as it approaches the core strand wire. The plastic strand formation method by means of a rolling head is presented on the left in Fig. 1. The swaging method is presented on the right in Fig. 1, while its bottom part displays the structure of two example strands with linear wire contact in arrangements before and after compacting.

The result of the compacting process is the diameter decrease of strands and ropes formed from them, an increase of the strand and final rope cross-section compactness and obtaining a smoother external surface relative to ropes with conventional strands. This in turn improves the friction between the rope and the drum or pulley. It also increases the rope's resistance to corrosion. Furthermore, due to the limitation of empty space between the wires as a result of the area contact, the stress distribution on the interacting surfaces is improved. Images of possible compacted strand cross-sections are displayed in Fig. 2.

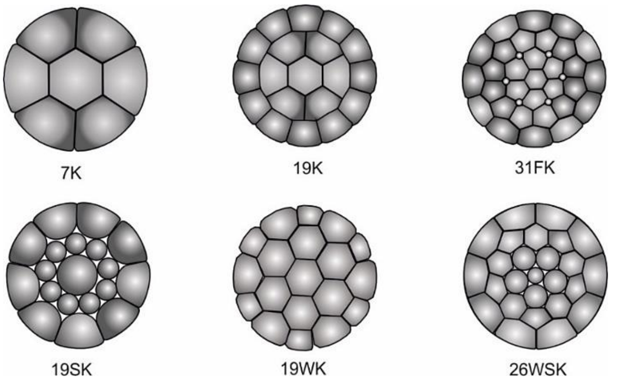
7K 19K 31FK
19SK 19WK 26WSK

***Fig. 2 Types of possible compacted strand cross-sections: from 7 identical wires, from 19 identical wires, Filer, Warrington, Seale and Warrington-Seale***

These drawings present typical (practically all) examples of strands compacted at high strain. The level of strain is not provided in the figure, as this parameter is omitted in the descriptions of ropes supplied by manufacturers. The compacting technology is also not provided, though these two factors, the strain and the technology applied, have a basic influence on the life of working compacted steel ropes. Photographs of an example compacted rope compared to its counterpart formed from non-compacted strands are displayed in Fig. 3. As can be observed, compacted ropes exhibit significantly smoother surfaces and better cross-section compactness. As a result, relative to equivalent ropes with conventional strand designs, compacted ropes exhibit lower uncoiling potential, lower rigidity and higher resistance to corrosion. These properties are very desirable in drum winches of all types, though they do not necessarily lead to an increase in fatigue life under mine shaft conditions.

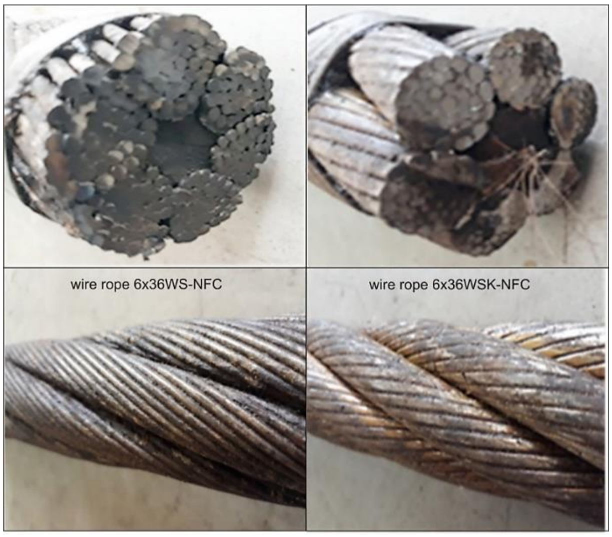

***Fig. 3 Views of rope cross-sections (top) and surfaces (bottom) for classic 6x36WS strands (left) and compacted 6x36WSK strands (right)***

Material fatigue is caused by oscillating bending stress as the rope runs over sheaves and by pulsating tension-tension stress during service [14]. Tests on a single wire show a large level of plastic deformation before the wire fails [15].

Steel ropes are continuously bent on drums and pulleys under cyclic loading and are subject to fatigue damage. Which are manifested by wire breaks. Fatigue wear is one of the reasons for ropes to be deposited in the operation process as well as the cause of accidents during improper use of ropes. The basic loads which occur are the tensile force and the bending load [16].

Fatigue occurs when a material is subjected to cyclical loads and is an irreversible and inevitable phenomenon in the process of use. Several fatigue life estimation models based on the Weibull statistical distribution, modified Wöhler curve and specified endurance function have been reviewed for applications in steel alloys [17, 18]. An integrated continuum mechanics model with a genetic algorithm was examined for the multiaxial fatigue response of steel samples [19, 20, 21, 22, 23].

Repeated stresses, even below the yield point, create microscopic cracks in the surface that eventually reach a critical size, causing the material to crack.

Fatigue progression is not detectable in the operational phase when they show no visible damage before reaching breakage of the wires [24]. Damage to steel ropes described in many literature items [25, 26]. Fracture mechanics has enabled design solutions based on the prevention of crack propagation [27, 28].

## STEEL ROPE FATIGUE LIFE AND ITS TESTING

Compacted ropes, i.e., ropes with compacted strands, are produced by few manufacturers, whose products are characterised by a very high quality of work and durability. They have found particularly good application as hoisting ropes for various types of cranes. The use of compacted ropes has particular significance in mining, where the life and operational safety of cranes are of primary importance. Ropes with a high fatigue life are preferred, but there is a lack of practical experience in using such ropes in mining applications. Therefore, tests comparing the fatigue life of compacted ropes with the life of similar and commonly applied conventional ropes are sensible in this regard from both the scientific and practical perspective.

The prediction of the fatigue life of steel ropes depends mainly on the results of non-destructive and destructive fatigue tests [29].

The fatigue tests in question were conducted at the Central Mining Institute's Laboratory of Ropes and Shaft Equipment in Katowice, Poland. They were prepared and carried out as part of a dissertation [4]. The tests were performed using P4-GIG-2 and P5-GIG-3 fatigue testing machines, depending on the diameter of a given tested rope. Ropes placed in these devices undergo two-directional (biaxial) bending at a static or cyclic bending force. The machines comprise a rotational mechanism by which the tested sample rotates around its axis. A view of the P4-GIG-2 fatigue testing machine is presented in Figure 4, while Figure 5 displays its kinematic diagram and Table 1 lists its basic technical parameters. This machine is intended for the fatigue testing of ropes at a diameter range of Ø40 mm to Ø65 mm. A tested rope's length between the grips is 6.5 m, whereas the length of the rope section undergoing bending ranges from 4.6 m to 5.0 m and depends on the bending wheel diameter. To prevent rope overheating and grease melting, the machine is equipped with an assembly for cooling the rope during testing.

***Fig. 4 View of the P4-GIG-2 fatigue testing machine***

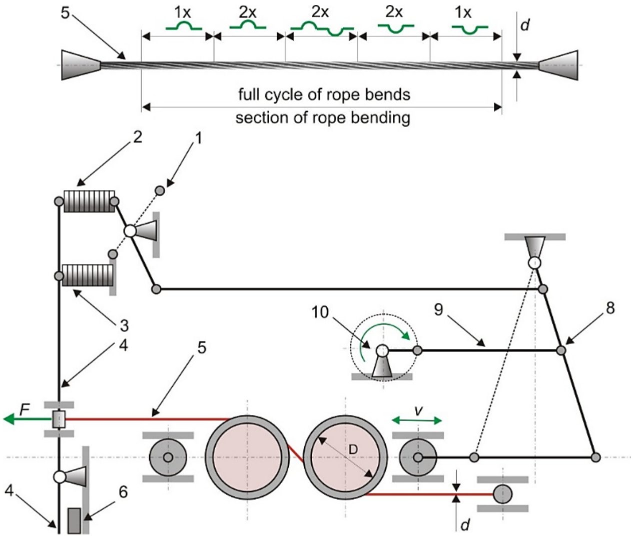

***Fig. 5 P4-GIG-2 fatigue testing machine kinematic diagram: 1 – top rocker; 2 – dynamic spring; 3 – tensioning spring; 4 – rear rocker; 5 – tested rope; 6 – middle rocker; 7 – stopper beam; 8 – front rocker; 9 – link; 10 – drive***

*Source: [29].*

Ropes with diameters ranging from Ø14 mm to Ø25 mm were subjected to fatigue testing by means of the P5-GIG-3 machine presented in Fig. 6. In terms of its function and construction, this machine is similar to the one described above, where the differences between the two lie in the different ranges of tested rope diameters. The machine's technical parameters are listed in Table 1.

***Fig. 6 View of the P5-GIG-3 fatigue testing machine***

***Table 1***

***Basic technical parameters of the P4-GIG-2 and P5-GIG-3 fatigue testing machines***

| Parameter | P4-GIG-2 machine | P5-GIG-3 machine |
|---|---|---|
| Sample length between grips | 6.5 m | 2710 mm |
| Bent section length | 4.6 m ÷ 5.0 m | 1550 mm |
| Machine trolley stroke | 2.0 m | 0.8 m |
| Wheel diameter to rope diameter ratio D/d | 30 | 30 |
| Rope wrapping angle on the wheel | 62°÷65° | about 60° |
| Tested rope diameter range | Ø40 mm ÷ Ø65 mm | Ø14 mm÷Ø25 mm |
| Fatigue cycle unit rate | 10 cycles/min | 26 cycles/min |

A rope mounted in the grips was loaded with static and cyclic forces obtained by means of a pair of springs – tensioning and dynamic (Fig. 5). The load value depends on the rope structure and diameter and is selected based on load parameter tables provided in the machine documentation. Cyclic loads cannot exceed 25% of the static load value. During testing, the ropes are subjected to tension consisting of constant and variable values. Over one cycle, the middle part of a rope undergoes double bending on the cable wheels (Fig. 5). The ropes were cooled during testing so that their temperature would not exceed 50°C as a result of internal friction. Each test was interrupted after a given rope ruptured, which corresponds to the rupture of at least one strand.

## CONVENTIONAL AND COMPACTED STEEL ROPE FATIGUE LIFE TESTING

The fatigue tests involved ropes with a conventional strand design as well as equivalent compacted ropes. The rope fatigue life was determined over the course of the tests as the number of cycles withstood by the rope until its failure. Periodic pitch length and diameter measurements were carried out during testing. The location and number of visible fatigue fractures and the rope elongation were registered as well. Fig. 7 presents a view of a rope section with fractured wires between the cable wheels of the P4-GIG-2 fatigue testing machine.

***Fig. 7 View of a rope section with fractured wires between the cable wheels of the P4-GIG-2 fatigue testing machine***

The test results were prepared in graphic form as charts presenting the rope elongation and wire fracture accumulation as a function of the number of fatigue cycles. Figures 8 to 10 display the fatigue life test results for various rope designs. The top parts of the figures show charts of visible wire fracture number growth, while elongation charts of both the compacted and conventional ropes can be found in the bottom parts. Fig. 8 presents the results for relatively thin ropes with a diameter of 18 mm.

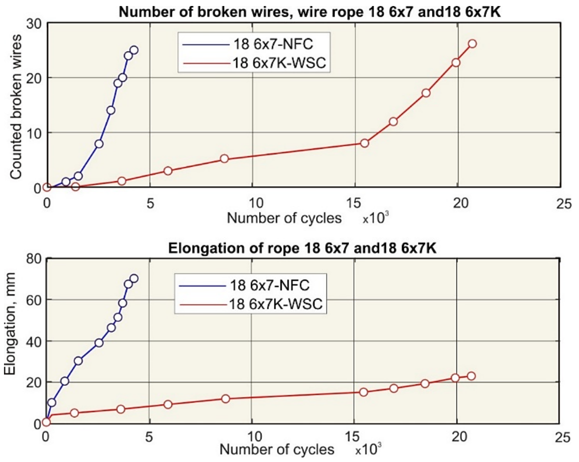

*Fig. 8 Fatigue life and elongation of 6x7 fibre core ropes with a diameter of 18 mm*

These ropes are an example of an application in crane hoisting assemblies. Fig. 9 and Fig. 10 display the results obtained for ropes with diameters of 50 mm and 60 mm respectively.

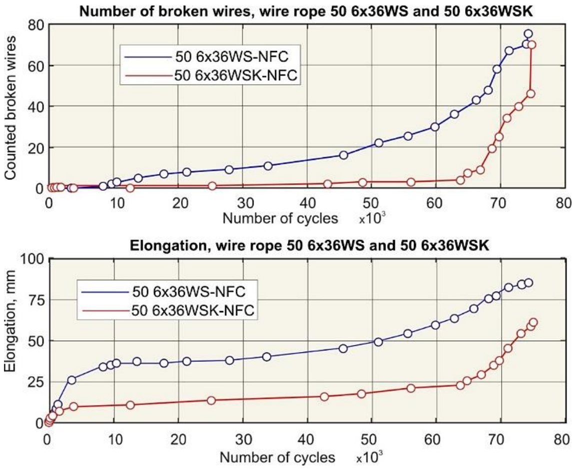

*Fig. 9 Fatigue life and elongation of 6x36WS fibre core ropes with a diameter of 50 mm*

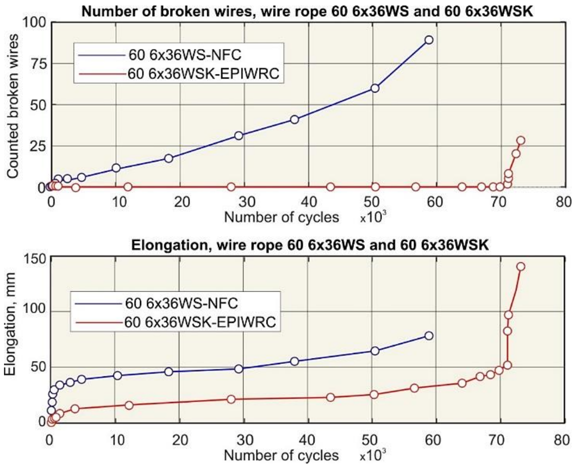

*Fig. 10 Fatigue life and elongation of 6x36WS fibre core ropes with a diameter of 60 mm and in the form of an independent plastic-coated rope*

These ropes, with a WS strand structure, are a good example of an application in mine shaft drum hoists.

The presented results demonstrate that compacted ropes are characterised by the greatest fatigue life. In these ropes, factors such as the wire area contact, the lower internal friction (particularly in ropes with plastic coated cores), the smoother surface ensuring better interaction of the rope with the wheel on which it is wrapped, and the thicker external layer wires all have a beneficial influence on decreasing the rate of the fatigue processes occurring in the ropes. The characteristic of the elongation function course depending on the number of performed cycles is completely different for ropes formed from conventional and compacted strands. The most significant feature of the elongation course characteristics for compacted ropes is the occurrence of three different and clear phases of the elongation process. The bending load, variable tension and wire fracture of wires induce relative slips between the rope and friction pulley, between contacting strands and between neighboring wires, which causes the wear of steel wires in the rope [30, 31]. The evaluation of the stress state in rope wires can be and how several assumptions and approximations are often necessary to predict rope duration under cyclic loading [32].

To conclude, it can be stated that the initial deformation process during the rope and strand production stage led to the equalisation of stresses in the individual strand layers, which in turn affected the increase in fatigue life. Obtaining area contact of the wires in the strand layers and between the strands significantly impeded the fatigue processes, the wires began to rupture much later, and the fracture accumulation progressed more slowly compared to the ropes of equivalent structure where the wires were in linear contact. The compacted ropes exhibited lower elongation, which may be associated with potential savings with regard to the operation of these ropes due to the lower number of trimming procedures required to perform at the site. The clearly visible smoother rope surface, obtained as a result of the flattened shape of the external wires, also improves the interaction of the rope drum with the rope. This should in turn extend the life of the costly drum lining. These savings, in combination with the extended service life, should largely compensate for the higher costs involved in the purchase of ropes formed from compacted strands. The obtained results confirm that the tested rope fatigue characteristics are best described by the model expressed by formula (2). The results of fitting such models to actual fatigue wear courses, not presented in this work, indicate their accuracy to be greater than 90%, obtained with the coefficient of linear determination. It should however be noted that in the case of compacted ropes, the process is considerably explosive, which finds confirmation in digital fatigue wear models presented as the power formula [5]. The fatigue process follows a logarithmic curve [33, 34].

$$Zn = \mathrm{a} \cdot N^{b}, \qquad (2)$$

where:

*n* – number of fatigue fractures,

*a*, *b* – equation coefficients,

*N* – number of fatigue cycles.

## CONCLUSIONS

1. The initial strand deformation in compacted ropes has a significant influence on their fatigue life.
2. The wire area contact in compacted ropes leads to a higher fatigue life of these ropes relative to equivalent conventional ones.
3. The increase in fatigue life depends on a number of design factors (particularly the rope structure, its method of coiling, the number of wires in a strand and strands in a rope, the plastic coating and the wire diameter) and random determinants that are difficult to assess.
4. Compacted ropes with small diameters exhibit a considerably higher fatigue life compared to equivalent conventional ropes formed from strands with linear wire contact.
5. Compared to conventional ropes, the process of compacted rope wire fracture number increase is of an avalanche character, i.e. after a long period of operation with no fatigue wear symptoms, the number of fractures then increases very rapidly.
6. The process of wire fracture increase for conventional ropes can be estimated as a power function with a fairly gentle characteristic, which makes it possible to track the rope fatigue wear process rate.
7. The elongation characteristics for ropes formed from compacted strands exhibit three clear periods (phases): a short initial period with a sharp elongation increase related to the spooling of the new rope, a long period with stable elongation, and a final phase characterised by an accelerated elongation associated with the quickly progressing fatigue wear with an occurrence of a large number of wire fractures.
8. The rope elongation characteristics are strictly correlated with the fatigue wear.
9. The tested conventional ropes with WS strands with diameters of 50 mm and 60 mm do not exhibit a clear advantage in durability over the compacted ropes (likely as a result of the compacted rope quality of manufacture).

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