A COMPARISON OF NON-DESTRUCTIVE DEFECT DETECTION METHODS FOR STEEL WIRE ROPES

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Steel wire ropes are among the essential technical elements widely used in many industries. The impeccable condition of these elements has a major impact on the safety of entire facilities where they are applied, be it construction, mining, agriculture, transport, engineering or another area. This article focuses on comparing two non-destructive methods designed to study the internal defects of steel wire ropes. They are defectoscopes with different principles of operation, namely the MID-3 magnetic defectoscope with both excitation and detection of the magnetic field by means of induction coils, and the REMA defectoscope with Hall sensors. Four reference samples of steel wire ropes used in underground mines with well-defined defects corresponding to damage due to fatigue of the wire rope material were created for the study. Based on the experiments performed, it was confirmed that defectoscopes working on the principle of Hall sensors can detect metal cross section loss adequately.

Keywords

Steel wire rope, Hall sensor, magnetic non-destructive testing, defect

1. INTRODUCTION

Wire ropes are the basis of many equipment and construction elements that we encounter in everyday life. Wire ropes are made of steel wire heat-treated in an oil bath (patented), and are characterised by high strength, relatively low weight and sufficient flexibility [Debeleac 2020, Liu 2020, Zhong 2012, Zhou 2019, Zhou 2021]. These properties guarantee the high load-bearing capacity of these ropes. During operation, the ropes are affected by many negative phenomena which reduce their service life, and these phenomena have an essential impact on the safe use of these technical elements. Defective, damaged or corroded ropes with a load-bearing capacity below the prescribed limits must be disposed of immediately. [Tomaskova 2018] Wire ropes are important safety components and need to be regularly inspected, as human lives often depend on their faultless operation.

The two main factors are corrosion and deterioration of load-bearing capacity. [Liu 2020, Nemtsov 2017, Nguyen 2021] The basic problem in detecting defects is seen to be in the damage that occurs on internal fibres and which is therefore not identifiable by visual inspection. The study and detection of defects and the associated changes in the load-bearing capacity of the ropes is carried out not only through a number of experimental techniques, but also via mathematical modelling. Several publications focus specifically on parametric computer models for rapid non-contact analysis, both static and dynamic [Liu 2020, Maliaars 2021, Zhang 2021]. Wire ropes are complicated mechanical components and their study must be carried out using finite element methods. Finite element methods can also be used to simulate the mechanical properties of worn fibres subjected to tensile loading. Results show significant plastic deformation and an apparent temperature rise in the defect region. There are a number of experimental techniques that can be used for the non-destructive testing of materials, such as ultrasound or X-rays. However, in the case of testing wire ropes, the only method that provides relevant results in practice is the magnetic-based method [Kaur 2018, Zhang 2019, Zhang 2020].

2. MATERIALS AND METHODS

2.1 The preparation of reference samples

The reference samples were prepared from steel cables commonly used in underground mines. A model of the cross-section, including a photograph of the actual material used, is shown in Fig. 1. These are patented steel wire ropes of a 6 x 31 WS - SFC1770 B zZ construction (6(1+6+(6+6)+12)+v, 186 wires in total, Seal-Warrigton). They are manufactured according to EN 10264-3. The nominal diameter of the rope is 37.5 mm. All reference samples were created from a single shortening to the length required for our 4 m stent. The defects on each reference sample were created by cutting the individual wires.

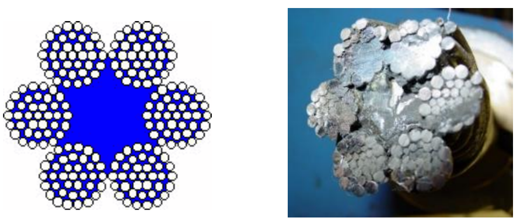

Figure 1. A cross-section model and actual photo of the used wire rope

Two defects were created in the first reference sample (R1) with a total length of 4000 mm (Fig. 2). Two internal wires with a diameter of 2.36 mm were cut in one cross-section at a distance of 1150 mm from the left end of the rope, i.e., a decrease of 1.6 % in the load-bearing cross-section. The second artificial damage was located at a distance of 1250 mm from the right end. This time, only a single internal wire with a 2.36 mm diameter was cut. In this case, the decrease in the metal cross-section was 0.8%.

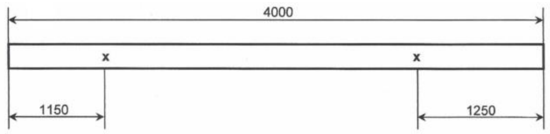

Figure 2. A diagram of reference sample R1, including the recorded defects

Figure 3. A photo of reference sample R1 and a photo of the artificially created internal damage

For reference sample (R2) with a total length of 4000 mm, a single internal wire with a diameter of 2.36 mm and a length of 250 mm (Fig. 4) was cut out, resulting in a 0.8 % decrease in the load-bearing cross-section. An image of the removed wire section in the inner part of the rope is shown in Fig. 4.

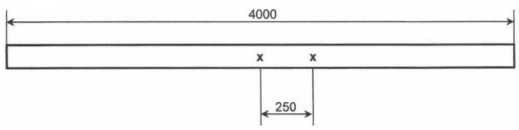

Figure 4. A diagram of reference sample R2 and the artificially created internal damage

In the case of the third reference sample of the damaged wire rope (R3), a wire with a diameter of 2.36 mm was broken inside the rope at a distance of 1200 mm from the left end of the rope (Fig. 5a), i.e., a decrease of 0.8 % in the load-bearing cross-section. Further damage was created in this sample by cutting out a wire with a length of 30 mm from inside the rope, i.e., a decrease of 0.8 % in the cross-section.

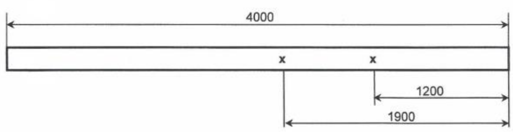

Figure 5a. A diagram of reference sample R3.

Figure 5b. A photo of artificially created internal defects

The last reference sample with artificial damage is marked R4 (see Fig. 6) and contained a defect in the form of a 300 mm long section of wire removed from the middle of the rope.

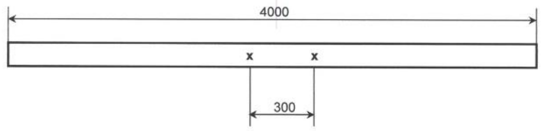

Figure 6: An illustration of reference sample R4, showing artificially created internal defects

2.2 The defectoscopes used

REMA defectoscope

The REMA defectoscope was designed and developed at the Technical University of Ostrava. This device consists of a magnetization head, an indication module and a desktop computer. The original version contained one channel for small-scale local defects (broken wires) and another for metallic cross-sectional losses (defects of about 700 mm or more). This version has been used in this publication. As some defects were in the millimetre range, a channel for micro defects was added in the next version. Finding such a small defect gives us information on which part (area) of the rope to focus on in more detail during further inspections. In addition, the defectoscope has a corrosion channel, which is characterised by the largest axial spacing as it has sensing elements at the extreme positions of the body. The magnetic circuits of the break channel are located in the centre, while the microtear sensor is located in the left part with a trio of signal outlets. Nowadays, smaller defects can no longer be detected due to the shape irregularities of the rope that arise during its manufacturing. Prior to measurement, the defectoscope is placed around the rope to be inspected, and the rope is then moved through the inner cavity of the defectoscope along its entire length (except for the beginning and end parts of the rope). A moving defectoscope, where the principle is reversed, also exists, i.e., the rope remains in place and moves through the defectoscope (this type of defectoscope is used sporadically). An increment sensor measures rope stationarity. It is important to take into account the proximity of ferromagnetic materials that would affect the measurement. A defectoscope forms a closed magnetic circuit with the rope on which it is mounted. The signal from the Hall sensors is transformed into digital data by an A/D converter.

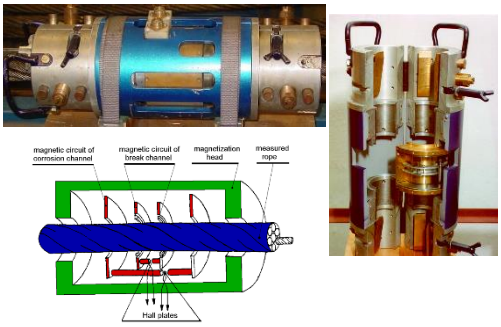

Figure 7. The REMA magnetic defectoscope and its model configuration used during experimental analysis

A diagram of the location of the Hall sensors in the inner cavity of the REMA defectoscope is shown in Fig. 7, bottom left. The technical parameters of the specific REMA-1 type used are detailed in Tab. 1 below.

Technical parameters of the REMA magnetic defectoscope	
Characteristics	Rema
Magnetic flux detection	Hall sensors with a diameter of 60 mm
Magnetic flux generation	Permanent magnets Nd-Fe-B
Number of channels	3
Magnetization	DC
Range of diameters of the measured ropes	18 mm, 25 to 60 mm
Maximum measurement speed	3 $m.s^{-1}$
Sensitivity	0,5 % change in the rope cross-section
Magnetization head weight	80 kg
Power supply	Mains / Battery

Table 1. Technical parameters of the Rema magnetic defectoscope

MID-3 defectoscope

The MID-3 magnetic defectoscope (see Fig. 8) was developed at the Institute of Coal Research in Ostrava-Radvanice, Czech Republic, in the 1980s. Technical parameters of this defectoscope are mentioned in Tab. 2. This type of defectoscope is still in use today; in a modernised and digitised form, naturally. Both the excitation (generation) and detection of the magnetic field are ensured by induction coils. Older types of devices used only one wide and one narrow coil for defect detection; newer defectoscopes have a larger number of both coils. At the turn of the millennium, many of these instruments were digitized. As they are robust, durable devices of simple construction, they are still frequently used in this country and abroad, especially in Slovakia. Along with the REMA defectoscope, both of these devices were used for test measurements at the University of Science and Technology of Brno – TUO laboratory.

Figure 8. MID-3 defectoscope

Technical parameters of the MID-3 magnetic defectoscope	
Characteristics	MID-3
Magnetic flux detection	Narrow and wide coil
Magnetic flux generation	Coil
Number of channels	2
Magnetization	DC
Range of diameters of the measured ropes	16 to 60 mm
Maximum measurement speed	1.5 $m.s^{-1}$
Sensitivity	1.5 % change in the rope cross-section
Magnetization head weight	20 kg
Power supply	Mains

Table 2: Technical parameters of the MID-3 magnetic defectoscope

3. EXPERIMENTAL RESULTS AND DISCUSSION

Comparative measurements of all reference samples were made using both defectoscopes under laboratory conditions. A manual feed, as smooth as possible, was used. Based on a comparison of the measurement results, it is evident that devices with Hall sensors better represent the real condition of the rope. Coil devices are influenced by their measuring principle. Although their sensitivity is high, Hall sensors better represent the condition of the rope, especially in the steel cross-section loss channel. It is possible to use a calibration based on added wire to obtain information on the condition of the rope. This condition is merely estimated for MID-3 type devices from the magnitude of noise.

Measured records of the individual samples are shown in Fig. 9-12.

Reference sample R1

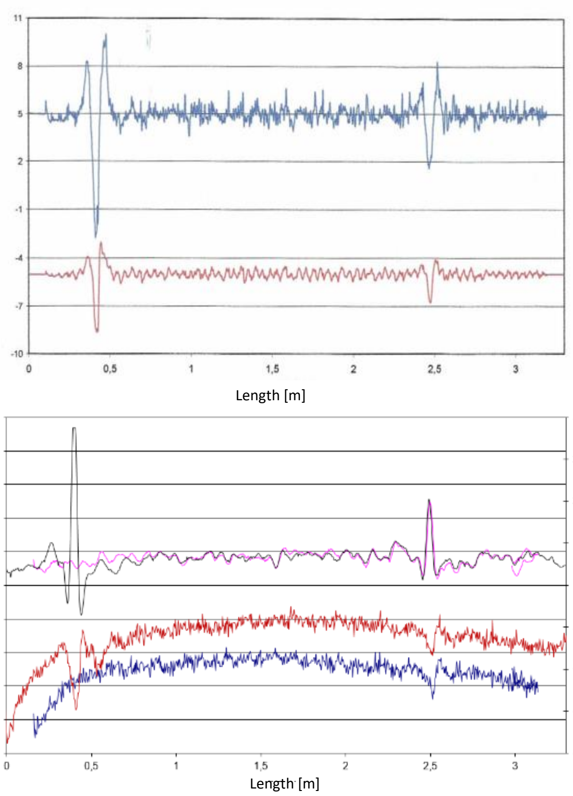

Figure 9: A record of reference sample R1 from defectoscope MID-3 (up) and REMA (down)

Reference sample R2

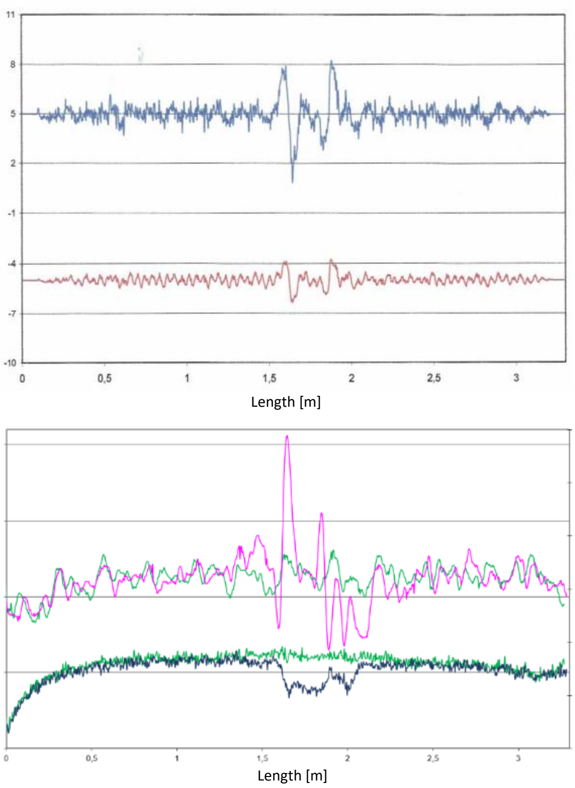

Figure 10: A record of reference sample R2 from defectoscope MID-3 (up) and REMA (down)

Reference sample R3

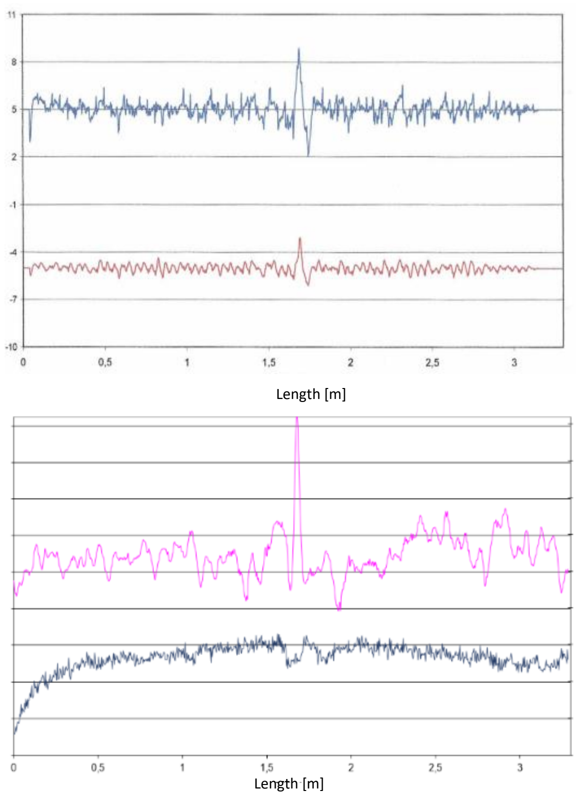

Figure 11: A record of reference sample R3 from defectoscope MID-3 (up) and REMA (down)

Reference sample R4

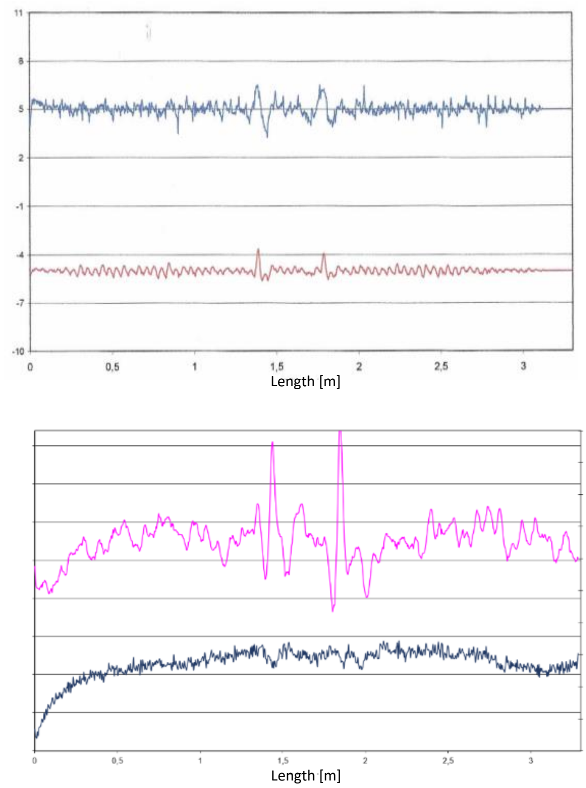

Figure 12: A record of reference sample R4 from defectoscope MID-3 (up) and REMA (down)

For each sample, the rope was measured with both types of defectors both at baseline and subsequently (and repeatedly) after the formation of defects. Calibration on a defined sample of rope without defects allows for the determination of the metal cross-section of the rope, in order to subsequently evaluate its loss due to artificially created local defects. For example, in the case of steel wire ropes used in mining operations, any loss of metal cross-section above 10 % means that the rope is immediately taken out of service, according to Czech Mining Office Decree No. 415/2003 Coll.

In the case of reference sample R1, the graph obtained with the REMA defectoscope shows the measurement result after the first damage to the inner wire (pink and blue curves) and after the second damage separately (black and red curves). Even in the defect channel, a difference between one and two broken wires is visible.

In the case of sample R2, the inner wire was cut out all at once; the measurement of the damaged rope by each defectoscope was therefore only performed once. The graph shows the measurements before the artificial defect (green curves) and after the defect was created to allow for a consistent comparison between these states. For this sample, the damage appears as two separate defects on the MID-3 defectoscope record, whereas the REMA clearly shows metal loss along the entire length of the defect created.

In samples R3 and R4, only the experimental measurement result for the final state after local damage is always given, for clarity. For both samples, the defects created are clearly visible.

The REMA device is able to characterize the loss of metal cross-section correctly only if it is longer than 700 mm; for shorter lengths the loss value is distorted. This is due to the design of the defectoscope and the arrangement of the small measuring horseshoes. This characteristic of the defectoscope is reflected in the record graph of reference sample R3. The defectoscope recorded the metallic cross-sectional loss, but its magnitude does not correspond to the real loss.

It is clear from all the records that the results of the measurement of the damaged ropes on the MID-3 defectoscope do not always show a significantly noticeable loss of metal cross-section. On the other hand, measurements with the REMA defectoscope are an advantage here; thanks to the Hall sensors we are able to accurately identify these losses and obtain information about local defects (material fatigue or wire failure/damage).

Two localised defects fully corresponding to the real condition are quite evident in the REMA defectoscope record of sample R4. The response of the MID-3 defectoscope is significantly lower than that of the REMA defectoscope, which has a much higher signal-to-noise ratio.

The REMA defectoscope records all show a signal rise, especially in the metal cross-section loss channel, which is due to the so-called end effect always associated with the analysis of finite length wire rope samples. The end effect issue does not affect the measurement itself, which can be utilised even for very short sections of wire rope. The rope end effect is shown in Fig. 13, which is a comparison of the magnetic induction line pattern for a model of an infinite rope compared to a rope of finite length, the end of which is less than 200 mm from the defectoscope. These images show a significant modulation of the induction lines, which is reflected by a significant signal rise in both channels.

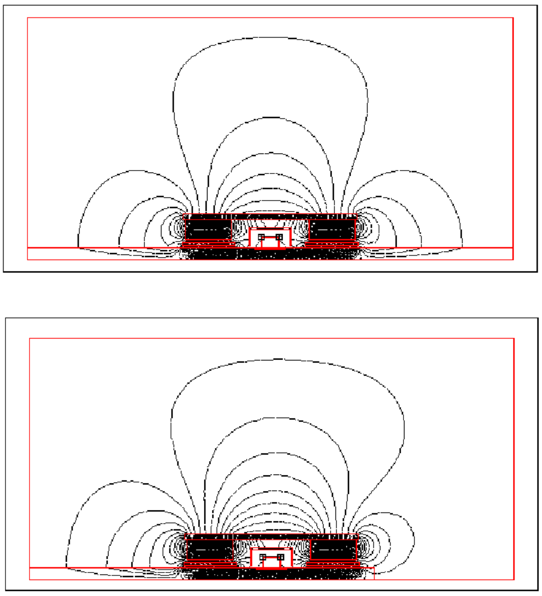

Figure 13: A model of magnetic field lines in the case of an infinite (up) and finite (down) rope

4. CONCLUSION

Four controlled experiments were conducted on steel cables with known defects. These experiments confirmed that the REMA defectoscope, which utilizes Hall-effect sensors, excels at detecting metal cross-section loss. It proved to be a highly effective tool for identifying defects and measuring metal loss in steel wire ropes. REMA's capabilities extend to calibrating the extent of metal loss, pinpointing the most critical (and potentially dangerous) section of the rope. This signifies that the REMA defectoscope, with its Hall sensor technology, can accurately detect all instances of metal loss and even glean information regarding hidden localized defects. This functionality is paramount for guaranteeing the safety and reliability of the ropes.

In contrast, defectoscopes like the MID-3 employ coils for magnetic field detection. These devices take an indirect approach to identifying metal cross-section loss. Rather than direct measurement, they rely on an increase in noise. A reduction in the cross-sectional area leads to a rise in noise levels. Consequently, the MID-3 defectoscope indirectly suggests a potential loss of metal cross-section. While this indirect detection can be useful, it lacks the precision of direct identification. Therefore, MID-3 defectoscopes can only indicate the possibility of corrosion, without providing an objective classification of its severity.

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