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Use of magnetic flux leakage detection in diagnostics of coated elevator ropes

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ABSTRACT

The aim of this article is to present the active magnetic method used in diagnostic tests to locate damage and determine the technical condition of flat steel-polyurethane cables and plastic-coated steel ropes used in lifting equipment. This article discusses the diagnostic equipment developed at AGH University of Science and Technology for magnetic testing of ropes in lifting devices. The results of tests conducted over the course of several years of operation of cables are presented. The changes in amplitude and signature of signals recorded during successive tests of selected flat steel-polyurethane belts are compared.

Keywords: diagnostics, passenger lifts, magnetic method, steel-polyurethane cables, active magnetic method.

INTRODUCTION

The continuous development of technical diagnostic methods and means today ensures an appropriate level of operational safety for machines, devices, and various types of technical objects. Modern diagnostic processes are applied to a wide range of technical systems, while older objects used in industry are adapted to changing standards and regulations. The most common parameters currently subject to continuous diagnostics or monitoring include temperature, speed, mass, flow, and stress. In the case of lifting equipment, monitoring parameters related to user comfort [1], operational parameters [2–4], and energy consumption is becoming commonplace to determine their energy efficiency class [5–7] and to provide a reliable approach to the problem of service life by examining lifting equipment components [8–10].

Understanding the processes occurring during operation and wear of ropes, their nature, and the rate of damage progression, using various diagnostic methods and tools [11], allows for the prediction of the duration and possibility of continued safe operation of a given lifting device and its individual components. This allows for the prediction of the approximate date of their replacement (shelving) due to excessive wear. Coated ropes used to move elevator cabins along the shaft are currently being tested primarily using the magnetic flux leakage method [12]. The problem of diagnosing steel-polyurethane cables using the magnetic method was discussed in publication [13]. The authors described the diagnostic system used and mentioned the need to develop acceptance criteria correlated with fatigue testing. In publications [14,15], the authors described the process of designing a prototype head for magnetic diagnostics of steel-polyurethane cables. The results of a series of numerical analyses were discussed, which led to the optimization of the magnetic circuit in terms of functionality and metrology. Work is also underway on the construction of complete systems for the detection, localization, counting, and classification of damage in steel ropes based on the measurement of magnetic flux leakage and signal processing and classification, enabling the development of new integrated diagnostic systems [16].

Currently, flat belts consisting of steel cables embedded in a polyurethane matrix, as well as steel cables coated with a plastic coating, such as PVC, polyamide (PA-6), and polyethylene, are very popular and widely used.

By using this type of load-bearing items instead of the previously common traditional steel ropes, elevator manufacturers have gained the ability to offer a new type of product – the machine-room-less elevator. Currently, machine-room-less elevators are offered on the market by both large and small companies. In addition to global companies such as Kone, Otis, Schindler, and Thyssenkrupp Elevator, manufacturers offering this type of solution also include smaller companies, and their number is steadily growing. A schematic diagram of a machine-room-less elevator is shown in Figure 1.

The main advantage of the machine-room-less system over traditional elevators offered to date is the gearless drive. It can be easily mounted on the cabin and counterweight guides inside the shaft, instead of in a separate machine room above the lift shaft. This winch is nearly 70% smaller than a gearless system, quieter (emitting noise levels of no more than 50–55 dBA, compared to 65–70 dBA for gearless elevators), and consumes less electricity than traditional drive units.

A machine-free elevator system provides architects with greater design freedom: it eliminates the need for an external covering of the elevator machine room, which consequently reduces the building's usable area or disrupts its utility lines with rooftop extensions. Using a machine-free system during the modernization of old elevators, however, allows for the recovery of an additional space previously used as a machine room and repurposes it for a more functional purpose for the building's occupants.

Thanks to these advantages, machine-room-less elevators are currently the main type of elevator installed in European Union countries and a widely used solution implemented worldwide. It is estimated that in Europe, they already account for nearly 75% of new installations introduced to the market and are slowly becoming the standard technical solution offered by all passenger elevator manufacturers.

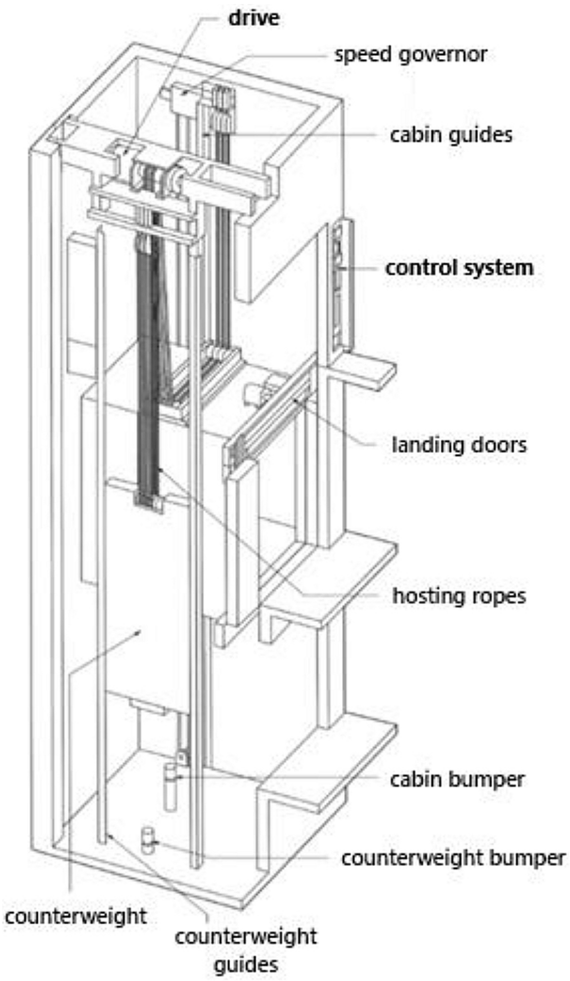

Figure 1. Schematic diagram of the elevator without a machine room [17]

However, this solution requires replacing traditional steel cables with new types of cables in the form of flat steel-polyurethane belts or steel ropes with a CTP polyurethane coating, for which diagnostics based on the visual method previously used for this type of equipment cannot be effectively applied.

CONSTUCTION AND DIAGNOSTIC METODS OF COATED ELEVATOR ROPES

Steel-polyurethane flat belts consist of steel cables embedded in a polyurethane matrix. Depending on the manufacturer and application, there are many different cable designs, varying in shape, external dimensions, number of cables embedded in the matrix, and diameters of the steel cables and wires. Examples of available flat belt designs used in passenger elevators are presented in Figure 2.

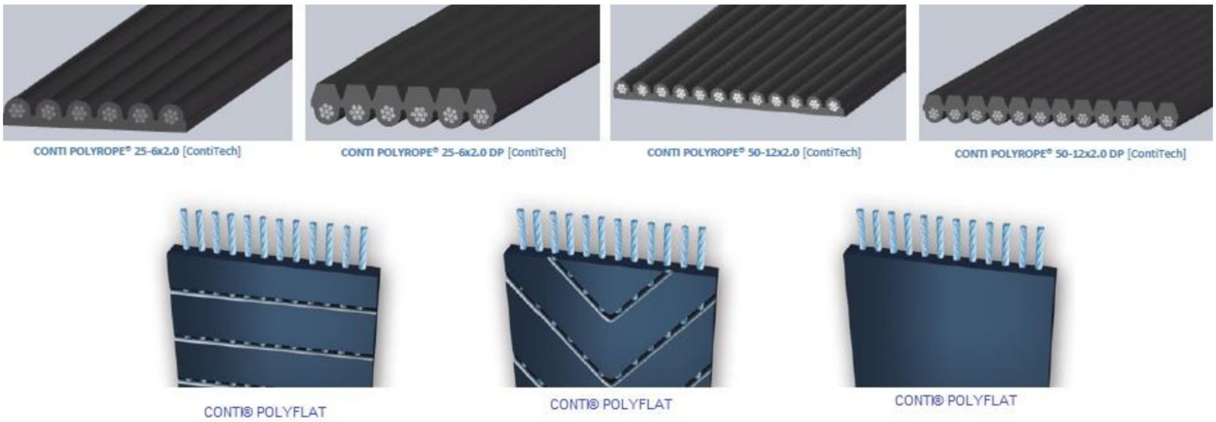

Figure 2. Shapes and cross-sections of sample solutions of flat steel-polyurethane belts [16,18]

Figure 3 shows an example of a belt consisting of 12 steel cables with a diameter of 1.6 mm, each cable consisting of 7 strands of 7 wires, which for a 30 mm wide belt gives a total of 588 wires with a diameter of 0.18 mm each.

The non-rotating nature of this design is achieved by alternating the cable arrangement in the strand with right- and left-hand lay directions (reducing the untwisting moments). The strands have a strength comparable to traditional steel ropes (e.g., for a 30 mm-wide strand it is approximately 36 kN), while at the same time they exhibit greater flexibility, allowing them to work with 100 mm diameter drive shafts (up to 80% smaller than the diameter of the drive wheels in traditional steel rope hoists). The use of a polyurethane carcass eliminates the need for strand maintenance, and the flat shape of the strand increases the contact area, which also significantly affects the stress distribution on the shaft surface of the gearless winch [20].

The most common method for diagnosing these types of passenger lift rods by maintenance technicians and inspectors from the Urząd Dozoru Technicznego is the so-called visual method – VT, according to the PN-EN 9712 [21] standard. Individual lift manufacturers provide guidelines for their equipment, describing the appearance of defects identified that require replacement. Examples of visually detected defects that require replacement are presented in Figures 4–6.

It should be noted, however, that when using the visual method in the case of flat belts, it is possible to assess the condition of the rope and the symptoms of damage only on its external surface (polyurethane surface) and the cables, but only when they leave the warp.

In machine-room-less elevator systems, in addition to flat steel-polyurethane belts, CTP-coated steel ropes (with a plastic coating) are also currently used. These are most often brass-plated steel ropes with a clear or colored plastic coating – material: C7(Mn+Si) steel + brass in PVC. A cross-section of an example CTP rope is shown in Figure 7.

In this case, the main advantage of this type of cable used to drive a passenger lift is a good coefficient of friction in kinematic pairs in which one of the elements is the rope, and the isolation of the steel (metallic cross-section) responsible for transferring loads from a possible corrosive environment and contamination.

In this case, using a visual method, it is possible to assess the technical condition of the CTP

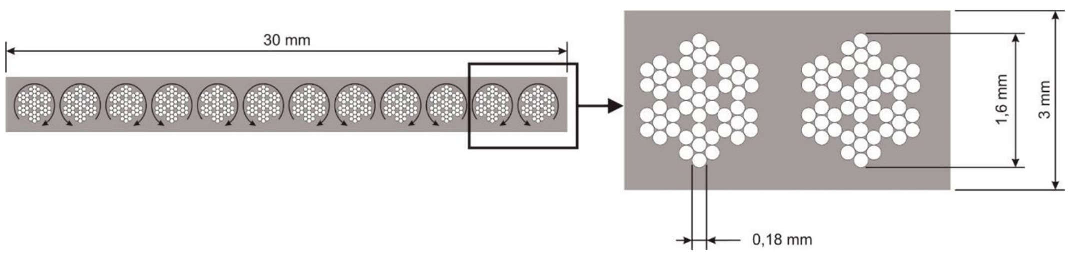

Figure 3. Construction of an example flat steel-polyurethane belt [20]

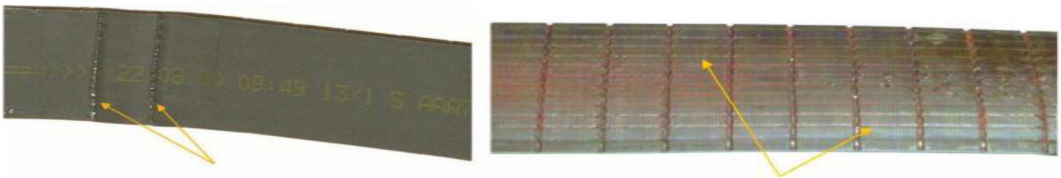

Figure 4. Deformation of the coating and imprints of the cables along the belt [22]

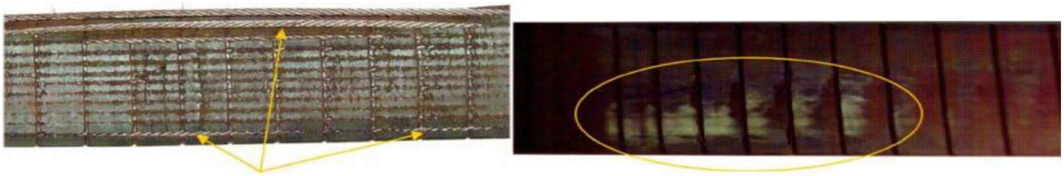

Figure 5. Cable protrusion and surface polishing on the belt shell [22]

Figure 6. Corrosion symptoms and protruding wires [22]

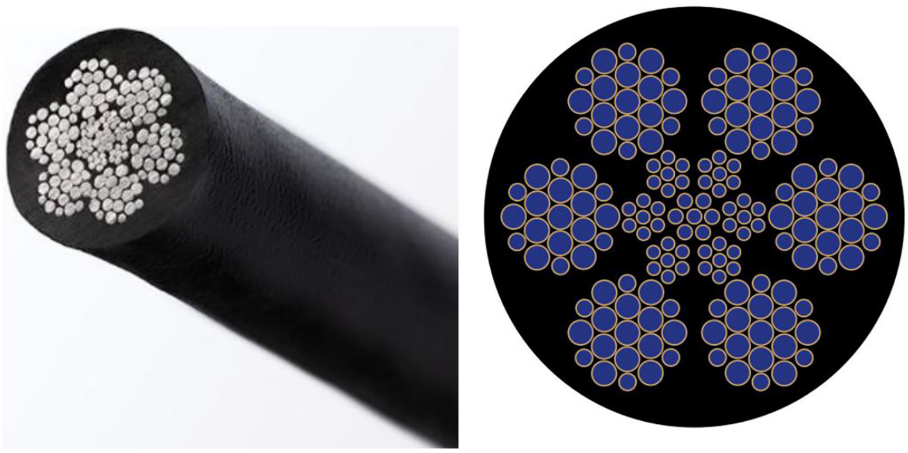

Figure 7. Example cross-section of a Brugg CTP type rope [20]

rope solely based on signs of wear observed on its external surface. The presence of broken wires can be detected when they penetrate the PVC warp. Figure 8 presents examples of operational damage to the wires in a CTP rope.

To locate faults in individual wires of steel cables within a flat steel-polyurethane belt or individual wires in CTP-coated ropes, numerous magnetic head solutions have been developed and successfully implemented for diagnostics of various cable structures. These magnetic heads utilize the principle of local magnetization of the ferromagnetic structure under test with a constant magnetic field and the detection of a stray field (MFL). The magnetic circuit of the head consists of a steel plate acting as a magnetic jumper, on which symmetrically mounted, appropriately polarized, strong permanent magnets, and a pole piece [23]. This arrangement of magnetic circuit elements, while ensuring sufficiently high magnetic energy, enables local magnetization of the tested strand structure to a level above B = 1.4 [T], which

Figure 8. Damage to the wires of the CTP rope

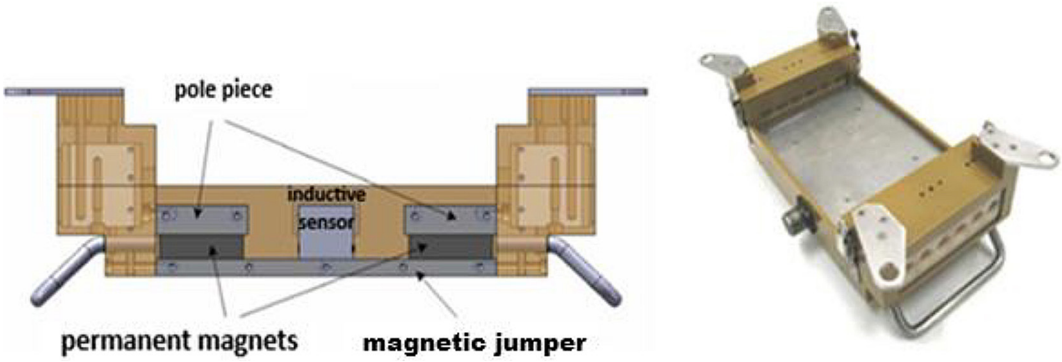

Figure 9. Model and prototype of the head for testing CTP coated ropes [19]

positively impacts defect detection [16,23]. At the location of damage to the steel cable, a stray field is created over the tested structure. The magnetic field lines deflect, "bypassing" air gaps (where the metallic cross-section is damaged, e.g., cracks, abrasions, etc.). This influences the direction of the leakage flux vector above the damage site and the value of its radial component. The change in this parameter's value over time is detected by inductive sensors, then converted into an electromotive force and recorded by a recorder. To test the entire length of the rope and induce an electromotive force in the sensor, the head and the ropes are in relative motion (in passenger elevators, the head is installed stationary). Inductive sensors (measuring coils) are located in the centre of the head. A model and prototype of the head for testing CTP-coated ropes are shown in Figure 9, and prototypes of the heads for testing flat steel-polyurethane tendons are shown in Figure 10.

MAGNETIC TESTING OF STEEL-POLYURETHANE FLAT BELTS

The presented test results for steel-polyurethane belts were conducted over successive years of operation on two different elevators equipped with the same type of cables. The tested belts, with an external dimension of 30 × 300 mm, were composed of 10 steel cables, each consisting of 49 wires. The belt had a total number of 490 wires, and its total metallic cross-section was 13.31 mm². The magnetic head developed at AGH (AGH University of Science and Technology), shown in Figure 10, and an MD121 recorder were used in the tests.

The magnetic head used in the research is made of a magnetic core consisting of a magnetic armature with dimensions of 195 × 70 × 10 mm, pole pieces (52 × 70 × 17 mm) and a magnetic field source in the form of two oppositely polarized NdFeB (neodymium-ferrite-boron) magnets with dimensions of 50 × 50 × 13 mm. Due to the need to locate discontinuities in the form of wire breaks in the head used in the tests, only inductive sensors covering the entire width of the tested tendon were used. Voltage signal acquisition was performed using an MD121 recorder with a sampling frequency of 1 kHz. Issues related to the design and verification of metrological properties, including the measurement uncertainty of the measuring head used, were widely described in the article [15].

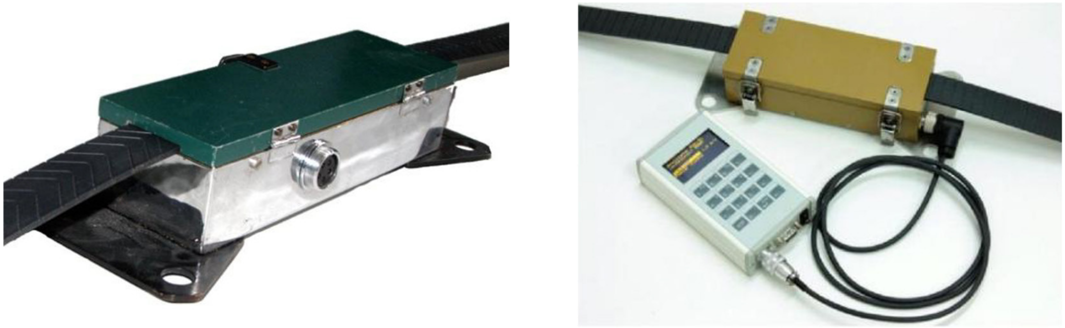

Figure 10. Prototypes of heads for testing flat steel-polyurethane belts [19]

The diagnostic system used in the study, consisting of a measuring head and an MD121 recorder, was verified through laboratory testing. During these tests, a signal was recorded on a belt with artificially created damage. Modelled damage, consisting of cuts of 3, 4, 5, 6, 7, 14, and 21 wires in one of the cables, was created at appropriate distances along its entire length. Verification of the modelled damage was performed using RTD digital radiography. An example image of the modelled damage with 7 cut wires, a radiograph of this location, and the voltage signal recorded during its magnetic testing are shown in Figure 11. Analysis of the obtained test results for the belt with modelled damage enabled the development of a calibration relationship for the diagnostic set. The relationship between the recorded voltage signal and the percentage loss of the metallic cross-section is shown in Figure 12. This relationship makes it possible to determine the percentage loss of the metallic cross-section of the tested tendon and, on this basis, to estimate the number of broken wires.

The processing of magnetic testing results is based on the analysis of the amplitude of the recorded signal as well as the nature of its shape (signature). Depending on the recorded signal signature, it is possible to determine the type of damage that generated it. An example signal from a single and continuous damage is shown in Figure 13. The signal amplitude and the calibration relationship of the diagnostic kit used allow for the determination of the percentage loss in the metallic cross-section of the tested ropes (ΔS_{Fe}) and the estimation of the number of broken wires.

The measurement, with the head fixed at the drive wheel of the tested lift (Figure 14, Figure 15), was performed while the cabin was traveling at inspection speed (approximately 0.4 m/s) along the entire path between the lift's limit switches in the shaft. This enabled recording of a diagnostic signal over a distance of approximately 29 m (lift no. 1) and 31 m (lift no. 2). Figures 16 and 17 show the voltage signal recorded during testing of the steel-polyurethane belts of the tested lift equipment.

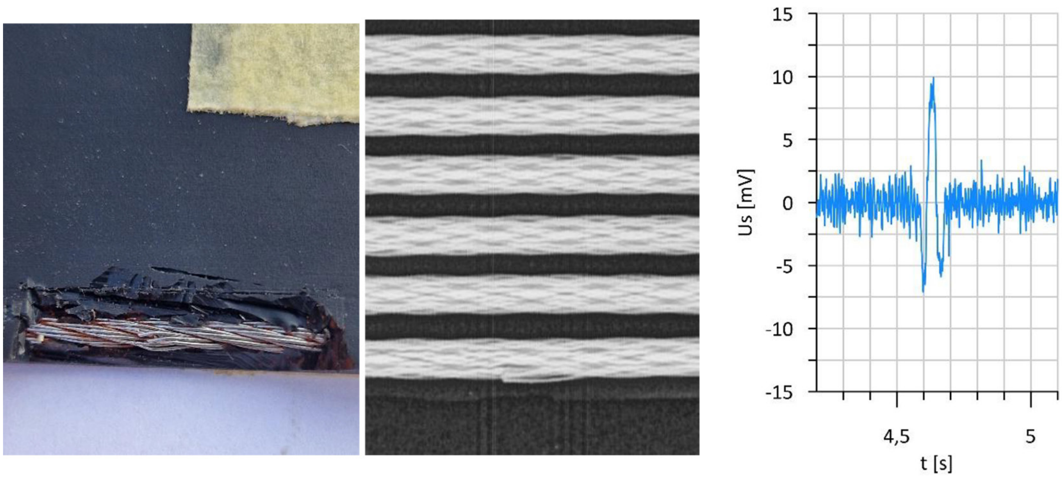

Figure 11. A modelled damage in the form of 7 cut wires, a radiograph of this location and a voltage signal recorded during its examination using the magnetic method

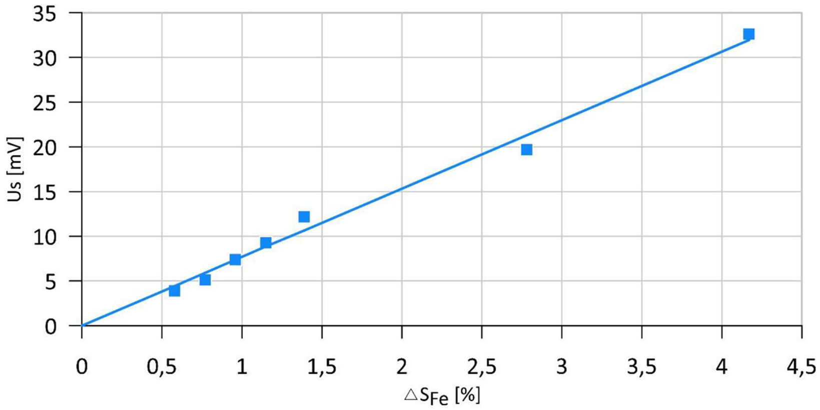

Figure 12. Calibration dependencies of the diagnostic set, dependence of the recorded voltage signal as a function of the percentage loss of the metallic cross-section [15]

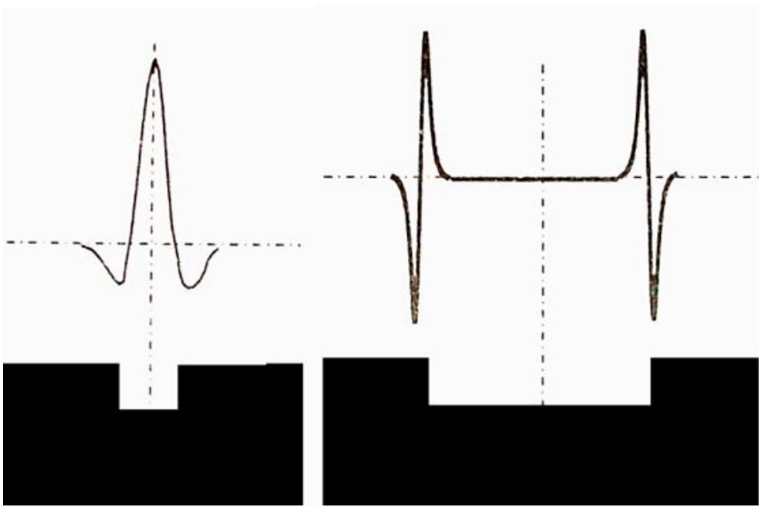

Figure 13. Examples of signal signatures from single and continuous damage [23,24]

In the results recorded on the first elevator (Figure 14, Figure 16), over a distance of approximately 21 m to 28 m, which corresponds to the cabin's position at the bottom of the shaft, changes in the amplitude of the recorded signal are visible. For the second elevator, the voltage signal from the belt test, recorded during the cabin's entire lift, is shown in Figure 17. At a distance of approximately 18 m from the start of the measurement, three diagnostic signals are visible, located close to each other. The changes in signal amplitude are associated with the occurrence of magnetic field disturbances, the source of which is loss of the metallic cross-section of the tested cables, e.g., cracks in wires embedded in the plastic matrix. A visual inspection of the indicated areas revealed no protruding wires, deformation, or other damage to the outer coating of the cable.

Figures 18–21 present a summary of selected locations on the tested belt of elevator no. 1 (Figure 16), illustrating sections of the belt characterized by signal changes in subsequent measurements taken at annual intervals during the tests in 2017, 2018, and 2019. The graphs presenting the results from subsequent years show changes in the amplitude and signature of the recorded signal. This indicates a change in the size of the observed damage, increasing losses in the metallic cross-section of the tested belt with continued operation, changes in the distance between the ends of the broken wires, or their displacement relative to each other and the matrix. The figures presenting the results of the tests conducted in 2019 also show new signals from subsequent damage events.

Figure 22 shows a fragment of the signal recorded on elevator no. 2 (Figure 17) during measurements conducted in 2021 and 2022. A change in the

Figure 14. Measuring head during the test of the belt (elevator no. 1)

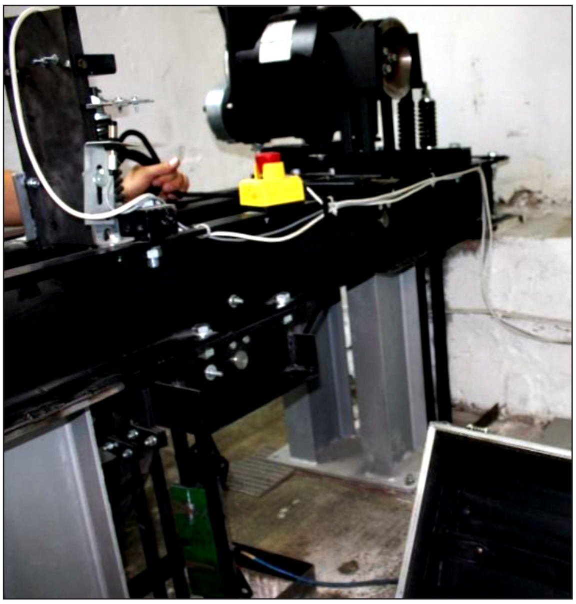

Figure 15. Measuring head during the test of the belt (elevator no. 2)

signal amplitude and signature is visible, resulting from the change in distance between the broken wires. A new signal is also visible from the third fault, located approximately 18.1–18.2 m from the beginning of the tested belt.

The results of the change in the metallic cross-sectional area of the tested belts (ΔS_{Fe}), determined based on the signal amplitude recorded during magnetic testing, are presented in Table 1. Analysis of the signal signature confirmed the presence of continuous damage and clusters of individual damages, which have been visible in recent years of operation: belt of elevator no. 1 at distances of 20.90 m and 21.65 m (Figure 18), and belt of elevator no. 2 at 17.09 m, 18.16 m, and 18.46 m (Figure 22).

Due to the current lack of standard criteria for the replacement of steel-polyurethane flat belts based on magnetic testing results, a criterion for replacement was adopted in consultation with the owner of the equipment: a maximum 2% reduction in the metallic cross-section for individual tendon damages. The occurrence of continuous or clustered damages also results in the termination of the belts service life.

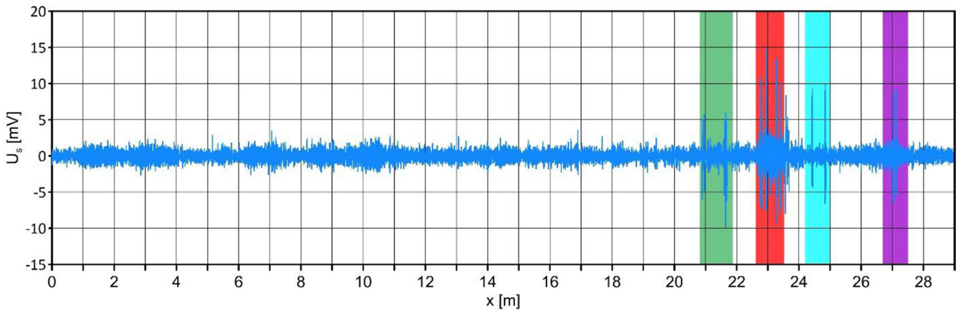

Figure 16. Voltage signal recorded during the test of the entire length of the belt (2019) of elevator no. 1

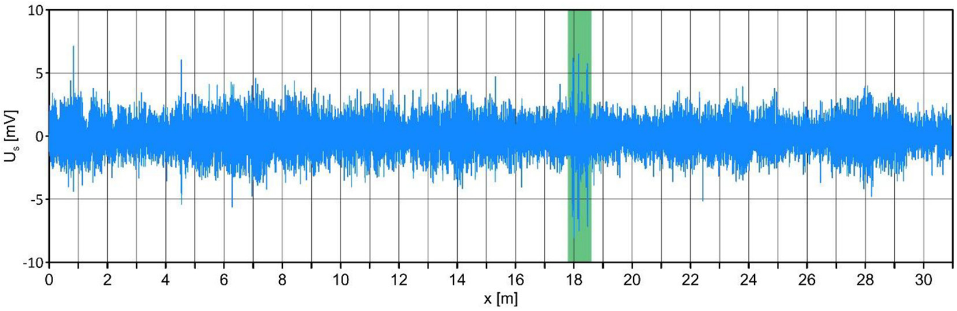

Figure 17. Voltage signal recorded during the test of the entire length of the belt (2022) of elevator no. 2

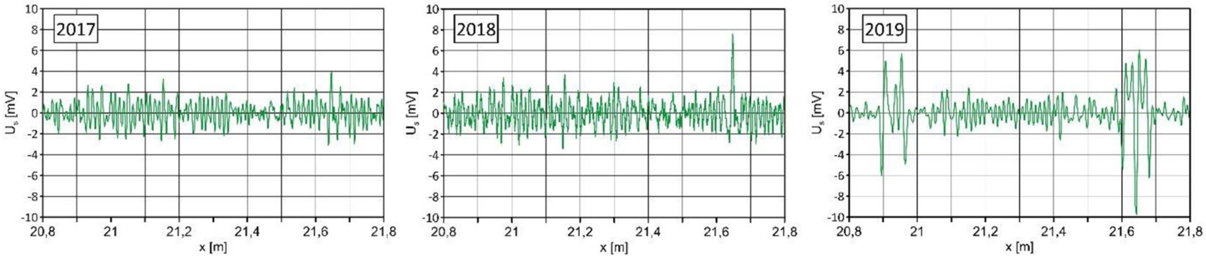

Figure 18. Fragment of the recorded signal in subsequent years of research (fragment marked in green in Figure 16)

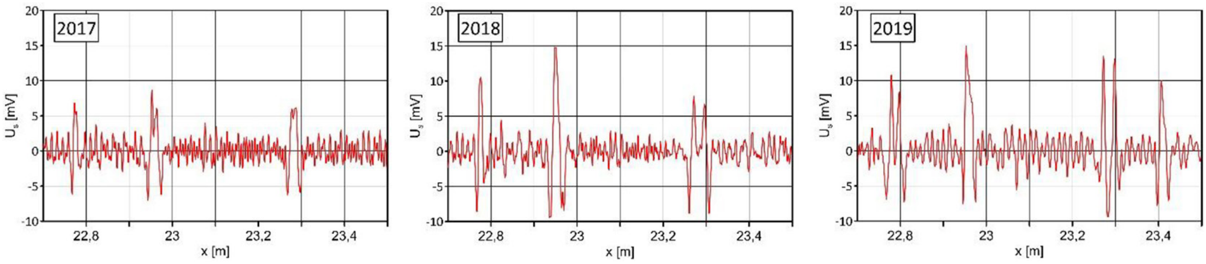

Figure 19. Fragment of the recorded signal in subsequent years of research (fragment marked in red in Figure 16)

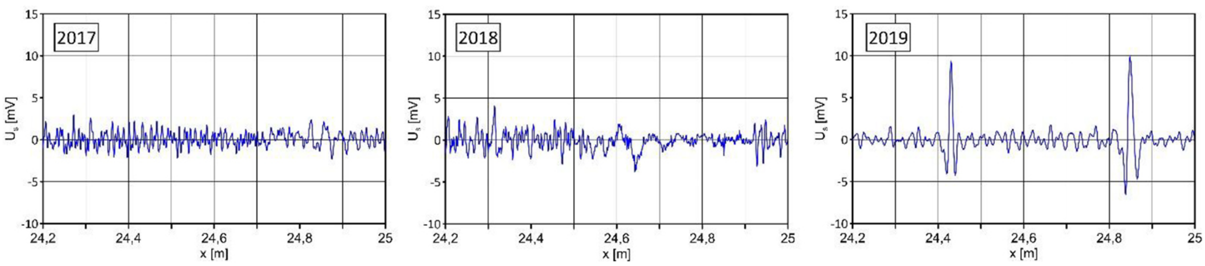

Figure 20. Fragment of the recorded signal in subsequent years of research (fragment marked in blue in Figure 16)

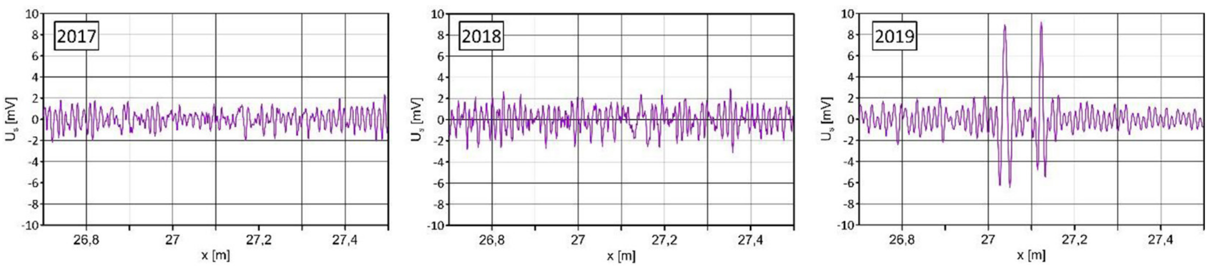

Figure 21. Fragment of the recorded signal in subsequent years of research (fragment marked in purple in Figure 16)

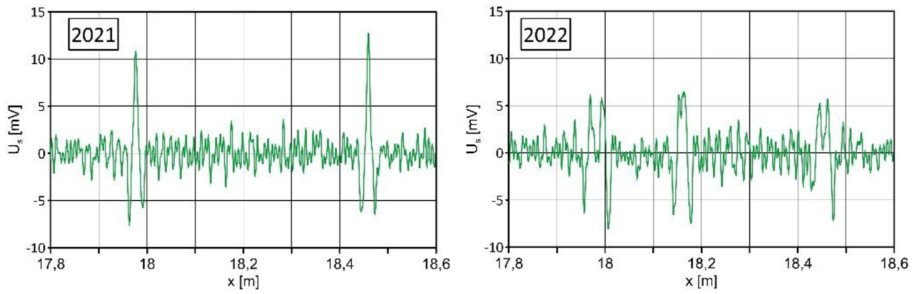

Figure 22. Fragment of the recorded signal in subsequent years of research (fragment marked in green in Figure 14)

Table 1. The results of the change in the loss of the metallic cross-section of the tested belts (ΔS_{Fe}) determined on the basis of the signal amplitude recorded in the magnetic tests

Belt of elevator no. 1							
Location of damage [m]		2017		2018		2019	
		ΔS_{Fe} %	Number of broken wires	ΔS_{Fe}%	Number of broken wires	ΔS_{Fe}%	Number of broken wires
20.90	Figure 18					1.8	9
21.65		0.5	2.5	1	5	2.8	14
22.76	Figure 19	0.9	4.5	1.3	6.5	2.5	12,5
22.95		1.2	6	1.9	9.5	1.9	9,5
23.28		0.8	4	1.7	8.5	3.6	18
23.40						1.3	6,5
24.42	Figure 20					1.2	6
24.85						1.3	6,5
27.04	Figure 21					1.2	6
27.12						1.2	6

Belt of elevator no. 2					
Location of damage [m]		2021		2022	
		ΔS_{Fe}%	Number of broken wires	ΔS_{Fe}%	Number of broken wires
17.98	Figure 22	1.4	7	1.5	7.5
18.16				0.9	4.5
18.46		1.5	7.5	1.5	7.5

CONCLUSIONS

The presented results confirm the application potential of the active magnetic field (MFL) testing apparatus described in the article. The active magnetic field (MFL) effectively reveals defects in the metallic cross-section of wires hidden in the polymer matrix. Thanks to local magnetization up to >1.4 T and the detection of the scattering field, it is possible to locate visually invisible defects. Knowledge of the structure of the tested strips (e.g., 10 strands × 49 wires = 490 wires, resulting in a total metallic cross-section of $\Sigma A \approx 13.31$ mm²) enables interpretation of the signal amplitude in terms of the equivalent cross-sectional loss and defect density per unit length, which is a necessary condition for trend-based assessment of service life. It concerns steel–polyurethane belts with various steel-strand constructions used in products manufactured by different companies.

Tests of the same belts performed in subsequent years demonstrate repeatability of signal locations and sensitivity to changes in their signature, enabling a quantitative assessment of damage progression over the adopted time intervals. The active MFL complements and extends visual ropes testing. Visual testing (VT) describes the condition of the coating and any punctures in the coating caused by previously broken wires, while the magnetic method provides information on the condition of the internal metallic cross-section in both steel-polyurethane belts and steel cables with CTP coating.

Using the same diagnostic equipment developed at AGH University of Science and Technology (AGH) to test lift belts operated on a real facility over several years allowed for the determination of the progression of defects in the steel-polyurethane belts. Implementing systematic magnetic flux testing reduces the risk of sudden failures and downtime, while the use of uniform equipment and procedures in subsequent years increases the reliability of comparisons of damage progression trends.

Currently, research using MFL detection is being successfully conducted at AGH on other types of steel–polyurethane belts used by various manufacturers of passenger elevators.

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