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THE SIGNIFICANCE OF NON-DESTRUCTIVE TESTING OF CRANE LIFTING EQUIPMENT

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Abstract: *Regular inspection and verification of lifting equipment is major to ensure the safe use of equipment. The inspection includes: visual inspection, dimensional testing, functional tests, equipment disassembly, electrical testing, and non-destructive testing (NDT). Materials that are used in the production of lifting equipment are liable to wear, deformations, cracks, and damage. Material fatigue or corrosion cracks are undetectable through visual inspection or disassembly, due to their characteristic of camouflage. Different studies showed that visual inspections are insufficient, so the focus should be on the direction of internal damage within certain components. Non-destructive testing is a method that can detect hidden defects in materials and elements. This research aims to show the classification of non-destructive testing, its advantages, the results of tests, and the most effective NDT methods for testing crane components.*

Keywords: *crane, inspection, lifting equipment, non-destructive testing*

1. INTRODUCTION

Cranes are defined as a machines of internal transport with periodic operation that are used to lift freely suspended loads on ropes/chains. Some cranes also move loads inside their manipulative space. The causes of incidents when working with cranes are numerous – from structural errors, through material errors and unexpected working conditions, to errors in the actual use and maintenance of cranes [1].

When conducting the risk assessment, risk factors such as incomplete inspection and review of work equipment, defects and damage to slings, clamps, hooks and other gripping devices are defined as micro-levels of risk that affect the safety of equipment and workers. By paying attention to them and taking suitable measures, there is a possibility of reducing risk factors [2].

To ensure the safety of lifting equipment, inspections and detailed examinations play a very important role. Their role is being fulfilled through inspections that can detect potential risks that can lead to accidents when working with the equipment, and to warn the owners about a certain defect that can lead to an accident.

Periodic controls and inspections are also necessary to check for corrosive damage and to determine the remaining period of use of the load-lifting elements in order to protect property, prevent breakdowns, and increase efficiency and legal requirements [3].

This research aims to show the classification of various types of inspection of cranes, where non-destructive testing (NDT) represents a method that can detect hidden defects in materials and elements. Also, the research will show the classification of NDT, its advantages, the results of tests, and the most effective NDT methods for testing crane components. This paper is organized as follows: section 2 show the types of examination and checking of crane lifting equipment, and then section 3 defines NDT testing of crane lifting equipment, types of NDT testing and the overview of existing methods, and results of testing crane lifting equipment, with a section 4 that concludes with recommendations.

2. TYPES OF EXAMINATION AND CHECKING OF CRANE LIFTING EQUIPMENT

In the Republic of Serbia, according to laws and regulations[4], cranes represent equipment that is subject to mandatory preventive and periodic inspections and checks of work equipment. Preventive and periodic inspections and checks of work equipment are defined as checking whether the safety and health at work measures, established by regulations in the field of safety and health at work, technical regulations, standards, and manufacturer's instructions, are fullfied on the given work equipment.
The Ministry of Labor of Great Britain [5] defines a detailed inspection as a visual and physical inspection, in addition to a functional inspection, to test the individual components of the lifting equipment. The main purpose of the inspection is to find out if there are any signs of excessive wear, tear, corrosion, cracks, overload, unusual sound, or vibration. The inspection will show if it is necessary to repair or replace the damaged components, or to put them out of service. Detailed inspection of the lifting equipment should also cover all accessories of the lifting equipment that are exposed to any damage and wear.
In order to ensure that lifting equipment is safe for use, it must undergo a thorough examination and verification, which includes the following: visual inspection, dimensional inspection, functional testing, equipment opening, electrical testing, and non-destructive testing (NDT). The main characteristics of basic types of inspections are shown in Table 1 based on a literature review [5, 6].

Table 1: Types of examination of crane lifting equipment

Type of inspection	Main characteristics	Performance instruments
Visual inspection	Includes checking and examining the condition of individual parts of the lifting equipment. The purpose is to identify any problems that may affect the integrity.	Unaided visual examination, hammer testing, magnifying glass, binoculars, endoscopes, borescopes
Dimensional inspection	Checking the dimensional tolerances of deformations of certain key components and configurations that significantly affect the stability, performance, and function of lifting equipment. The purpose is to ensure that dimensional tolerances are within the limits specified in standards and specifications.	Rulers, protractors, calipers
Functional testing	This test includes a no-load test and a load-bearing performance test, where: • a no-load test is performed first, to ensure the crane is capable and safe for the load performance test, • load performance test – to confirm the performance of the given lifting device (static and dynamic testing).	Load – such as concrete box, steel beams, or dynamometers

Equipment opening	This type of inspection includes checking covered, hidden, or wrapped components to check that they are within the limits recommended by the manufacturer's specifications.	Wrenches, spanners, cutting tools, screwdrivers
Electrical testing	Electrical tests are carried out by authorized electrical operators.	
Non-destructive testing	Method that can detect hidden defects in materials and elements.	Ultrasonic testing equipment, magnetic particle testing kit, radiographic testing equipment, vibration analyzers, infrared thermography cameras

3. NON-DESTRUCTIVE TESTING OF CRANE LIFTING EQUIPMENT

Materials that are used in the production of lifting equipment are liable to wear, deformations, cracks, and damage. Material fatigue or corrosion cracks cannot be detected by visual inspection or opening, and non-destructive testing should be used to assess the reliability of these parts. There are standard procedures, precise equipment, and technology for conducting NDT [5]. NDT tests should be performed as part of annual inspections to maintain lifting equipment in the best and safest condition [7].

3.1 Types of Non-Destructive testing

Non-destructive testing can be performed using the following methods: testing with liquid penetrants, testing with magnetic powder, electrical test methods, ultrasound examination, and X-ray examination. The short description of every NDT method is shown in Table 2 based on [6].

Table 2: Types of NDT testing

Non-destructive methods	
Testing with liquid penetrants	• The method is very simple, cheap, easy to perform, does not require a large volume of equipment; • It is used to visually improve surface cracks; • It is effective only for the inspection of small areas where surface cracks are suspected; • The technique is performed using liquid penetrants.
Magnetic powder testing	• Practiced worldwide for over 50 years; • Recognized as one of the most widely used and cost-effective NDT testing methods; • Implementation is easy and the principle is simple; • The technique is performed using alternating current, AC, a magnetic yoke or a permanent magnet set, and magnetic powder.
Electrical test methods	• It is used to detect surface and hidden damage, detect cracks, determine their sizes, and determine the thickness of the coating; • By measuring electrical changes on the surface damaged area, that are induced by eddy currents induced in the test specimen; • It is not suitable for the inspection of welded parts;

	• There are two additional methods of electrical NDT testing: • AC potential drop, • AC magnetic field measurement.
Ultrasound examination	• This method involves ultrasonic measurement of the thickness of a specific element; • It is the most commonly used method of testing steel structures; • It is done by using ultrasonic pulse-eco compression wave techniques and equipment that require a clean and smooth surface, and water or gel is used to ensure good energy transfer.
X-ray examination	• The principle of X-ray examination is simple – the material subject is placed between the radiation source and the photosensitive film; • It is mostly used when checking critical welded parts; • Since the overall procedure does not provide real-time data, it is likely that many defects will go unnoticed unless a very large number of photographs are taken.

In addition to the mentioned types of NDT testing, there are additional 5 testing techniques [6] whose use varies depending on the specific requirements of the industry, and these include:

- Acoustic emission testing – the oldest NDT testing technique, represents listening to the sounds of material damage using the release of high-frequency energy from structural damage when the structure is stressed beyond its normal operating limits;
- NDT testing for fatigue and crack detection – a form of NDT testing that can detect fatigue cracks while they are still at the microscopic level, by manually taking replicas using reproduction tape in areas where the greatest stress is expected. After the impression is made, it is stored on a glass microscope slide and taken to a laboratory for evaluation;
- Thermography (infrared thermographic techniques) – widely used to produce maps of infrared emissions from targeted areas, where thermographic cameras locate differences in temperature that indicate areas where corrosion or cracking has occurred, it is useful for checking elements for corrosion, cracks or coating thickness;
- Laser optical techniques – this method detects internal defects such as debonding, voids, and impact damage, this method measures surface deformations on the surface of the object being examined, where the surface must be viewed under two different voltage levels, and information at both levels is processed in a computer and interference patterns are projected onto a viewing screen,
- Vibration monitoring – it is used on simple structures to indicate changes in characteristics because a change in vibration characteristics usually indicates that some structural damage has occurred, represents an early detection technique that indicates the need for more detailed investigation in order to determine the cause of the change in vibrations.

3.2 Overview of existing methods and results of testing crane lifting equipment

The test performed using a flaw detection device with magneto-inductive sensors, was conducted to obtain a picture of the development of damage on the rope, 156 measurements were made on 39 cranes. The figure 1 (adapted from reference [8]) shows the course of damage on the crane rope in an interval that was approximately 3 months. During the initial test of the rope (Fig. 1a), no interruptions or technological connections of wires created during the production process were observed. The results of the NDT test after 69 days are shown in Figure 1b. The recorded results did not show significant changes compared to the initial test record. On the results of the NDT test after 162 days of operation (Figure 1c), the first internal damages were identified. Follow-up after 246 days is shown in Figure 1d. Recorded records show two groups of ruptures formed by a nest of internal wire ruptures. There were no external and visible cracks in the rope. The rope was removed after 246 days of work. The conducted NDT testing indicated that visual inspections that detect external breaks are ineffective and the focus should be on potential deformations and changes in the cross-section of the rope. Using NDT methods of magnetic-inductive testing techniques can help solve problems and risks when working with lifting equipment [8].

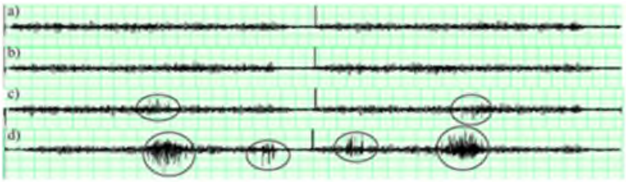

Figure 1: Rope damage progress - NDT records - the record shows both directions of rope movement in the defectoscope [adapted from reference 8]

In [9] seven tests were performed using rope samples with two different construction types. A test matrix was developed to obtain the most complete picture of the behavior of the ropes when exposed to constant bending under load. The ropes were tested at the following load levels: 330 t tension, 245 t tension, 165 t tension, 75 t tension. After the ropes were installed, they were tensioned to stabilize them before the fatigue tests. Throughout the test program, NDT magnetic tests were conducted to determine fatigue damage to the ropes. It was determined that most wire failures occurred within the rope, with no or very little visible signs of damage on the surface of the rope. Tests have shown that NDT testing (such as magnetic flux measurement) is essential for the inspection and review of grippers and lifting equipment and that the application of the ISO 4309 standard alone is not sufficient for a given rope.

Visual testing allows the detection of external damage, such as corrosion, and broken and missing wires if the surface of the rope is available for visual inspection. The visual examination can be accompanied by haptic testing, using a mirror, and a magnifying glass, and is performed with slow movement. The examination itself is very tedious, takes a lot of time, and is very subjective. It is important to note that ropes that are multi-layered, with low rotation, and widely used for lifting loads, begin to deteriorate internally, and internal broken wires cannot be detected by visual inspection. For this reason, researchers [10] point out that visual inspection combined with the use of magnetic instruments significantly increases the reliability of the information obtained from the tested rope. They state that magnetic flux rope testing - MFL, that is, testing instruments, can accurately and quickly measure the loss of the metal section to assess the level of abrasion and corrosion, but also detect external and internal cracks even under grease or protective coating.

The research [11] performed a visual inspection and an electromagnetic method as part of the inspection of steel ropes to detect abrasive action, and corrosion and detect broken rope wires using an electromagnetic testing device. The results of the electromagnetic test include the detection of broken wires in the rope, the effect of the sensitivity of the recorder, the effect of the length of the broken wire, the effect of the depth of the defect, but also the effect of corrosion and wear. Wear and corrosion are characterized by a reduction in the cross-section of the rope, while corrosion is often local and overlaps with other anomalies. The results obtained from the rope test are shown in Figure 2 (adapted from reference [11]). It is an area with high-pressure impressions combined with signs of corrosion. As a result, the background noise characterizing the overall response of the rope changes due to corrosion phenomena. Magnetic powder testing has been shown to be the best when testing lifting equipment, as it can quickly detect any defects without the need for paint removal or surface preparation [7].

Figure 2: High pressure area combined with signs of corrosion [adapted from reference 11]

Another research [3] examined an asymmetric gantry crane dating from 1970, installed in a power plant. However, the simultaneous presence of smoke and sea salt made the environment act aggressively on the coatings, which favored the occurrence of corrosion on the steel. In addition, the screws caused phenomena to occur in the cracks - corrosion developed in the interspace where the plates overlap, when the enamel coating was damaged due to the combined effects of atmospheric agents. The joint was mechanically damaged and subjected to NDT testing with magnetic particles and thickness measurements using an ultrasonic device. Magnetic inspection showed no evidence of significant defects in both the weld and the heat-affected zone. Several detected defects, mostly linear, were shorter than 2 mm. Plate thickness measurements showed a significant reduction (up to 50% of the original value) only in the crack zone at the overlap of the plates - where corrosion damage is characterized by oxidation and swelling of the plates, and away from this zone - the plates suffered a thickness reduction of about 6% in places where the protective paint was missing.

Laser scanning technology was used to check the geometric parameters of crane rails. The laser scanning technology showed comparable accuracy with the classical method, and the measurement and processing times were similar compared to the classical method. The test results showed that three parameters were exceeded: the tolerance in the distance of the crane rails, the horizontal deviation tolerance related to the test length of 2 m, and the vertical deviation tolerance related to the test height of 2 m. The experiment showed the usefulness and convenience of laser scanning technology for the purpose of checking the geometric parameters of crane rails [12].

Periodic NDT tests of the rails and tracks of the crane determined their condition, the type and nature of the defect, and its development. Defectoscopes reveal 99% of all detected defects on the rails and crane path. Analyzing common crane rail defects in Bulgaria, for the period from 2013-2016, shows the following number of cases of damaged rails: rail head defects (36), rail neck defects (1780), rail heel defects (58), rail cracking cross sections (32), rail deformation (12). Identified defects are most often subjected to NDT testing (visual, magnetic, ultrasonic, x-ray). An ultrasonic examination was performed to detect defects on crane rails by scanning the zone using appropriate personnel and devices. However, this method has several disadvantages, which are reflected in the low productivity of testing, the influence of the human factor, and the possibility of distorting the results when preparing the testing protocol. The UltrasonicInspection MF800C device was used for the ultrasonic inspection. The results of the ultrasonic test are shown in Figure 3 (adapted from reference [13]) and imply the detection of defects and the condition of the crane rails [13].

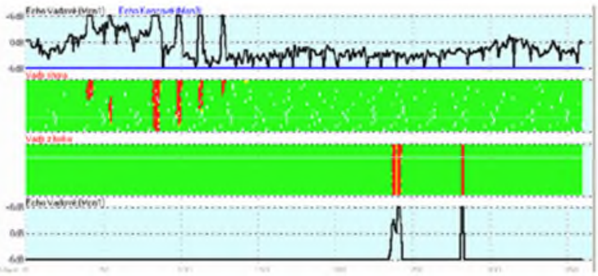

Figure 3: Results of ultrasonic testing of crane rails [adapted from reference 13]

Analysis of wire rope failures and damage was conducted using optical micrography, stereo micrography, chemical composition analysis using inductively coupled plasma atomic emission spectroscopy, hardness testing, and SEM/EDS analysis. During the visual inspection, a damaged core was found in the damaged rope, completely dry and unlubricated. During stereoscopic observations, samples from different strands of damaged wire rope were observed under a stereoscopic microscope. This type of observation showed damage caused by tensile loading- wear, friction, and fatigue damage. Fatigue damage due to abrasive action was also observed under the microscope. Also, when examining the rope, fractography was used, the results of which (Figure 4a-adapted from reference [14]) showed the damaged area and its two regions (zone A and zone B) at the inner broken end. Zone A shows striations indicating fatigue (Figure 4b adapted from reference [14]) and Zone B shows indentations (Figure 4c adapted from reference [14]) indicating failure due to tensile stress [14].

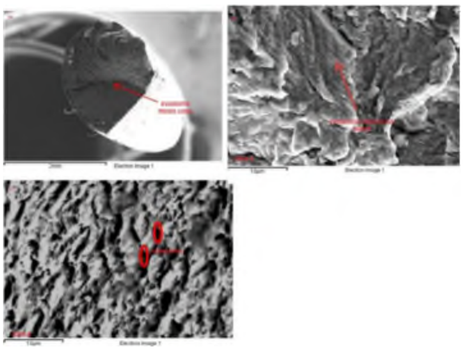

Figure 4: Fractography of the tested rope [adapted from reference 14]

A rotary particle depositor is a low-cost method of separating waste particles from an engine oil sample using a filter. Particle separation collects all contaminants in the sample, which can often lead to confusion during analysis. The mentioned technique allows the preparation of an oil sample for microscopy in approximately 6 minutes. When the samples were analyzed through a microscope, the following results were obtained in Figure 5 (adapted from reference [15]): looking from left to right, there are more fine particles in the sample, then, the mean particle sizes in the sample increased, resulting in the end in larger particles being visible in the sample shown [15].

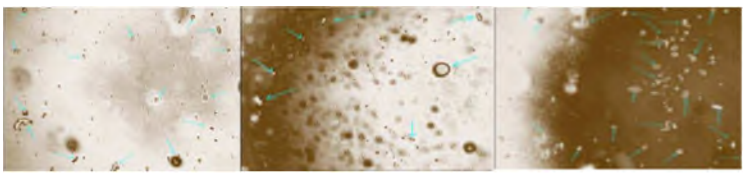

Figure 5: Results of microscopic examination of contaminants in the sample[adapted from reference 15]

From the above experiment [15], it is observed that the wear rate increases with the life of the Tire Mounted Crane. Adhesive sliding wear particles are present in most lubricants and are the result of normal wear. The particles are visible as thin asymmetric flakes of metal with highly polished surfaces. The presence of a few of these particles is not significant, but if their concentration is several hundred, it is an indication of serious wear in the engine. A sudden increase in the amount of wear particles indicates the possibility of failure. The experiment showed that oil analysis is the most effective technique for monitoring engine health.

There is also a remote and effective NDT test method using the thermoelastic effect technique to detect and assess the fatigue of beam girder cracks in a bridge crane. The thermoelastic effect technique involves the use of infrared thermography and through it has been proven that it is possible to measure stress with high accuracy, where the tip of the crack can be detected as an area of high temperature [16].

Comparing all the NDT testing methods, magnetic particle testing is the most effective method for detecting small surface cracks, while ultrasonic testing is effective in detecting internal flaws. Laser scanning technology is a modern useful method used in inspection of complex structures, where traditional testing is difficult.

In order to bring innovations in NDT testing, [17] proposed an automated robot MILA3D for the inspection of steel parts of structures, especially for the inspection of bridge cranes (Figure 6-adapted from reference [17]). MILA3D performs advanced detection of surface and subsurface cracks of different thicknesses and depths, as well as corrosive damage using NDT tests and Giant Magneto-Resistance (GMR) sensors. The MILA3D robot is characterized by a compact and flexible design, fully autonomous operation, data collection, and sending back to a remote location for real-time monitoring, as well as the ability to create a 3D map of the inspection area. The proposed method provides a significant contribution to overcoming the limitations of current bridge crane inspection methods by providing an economical and efficient solution using GMR sensors and NDT technologies. Advantages of MILA3D lie in reducing inspection time, enhancing the safety of the inspector by minimizing the human presence in risky areas, lower costs, and improved inspection solidity.

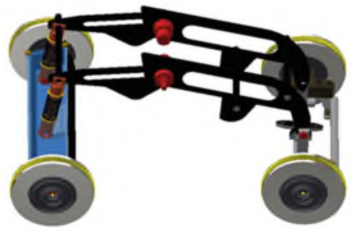

Figure 6: MILA 3D robot with GMR sensors [adapted from reference 17]

4. CONCLUSION

The risks that occur with crane lifting equipment, have shown the importance of proper maintenance and inspection of cranes. Lack of adequate supervision and investigation can lead to serious incidents in the form of fatal accidents and property damage. Conducted tests indicated that visual inspections are not sufficient, that they are ineffective, and that the focus should be directed on potential deformations and damages that occur inside a specific component, which are revealed through various NDT test methods. Within NDT testing methods, the most common methods used in practice are: the use of magnetic powder, electromagnetic methods, laser methods, X-ray methods, ultrasonic methods, use of thermographic cameras, and microscopic methods. The most effective method when testing crane parts is testing with magnetic powder because it allows all defects to be detected quickly without the need to remove paint or prepare the surface. A great advantage was also observed using the laser method when testing rails, due to the reliability and convenience of the technology, as well as the volume of data obtained. It is recommended that magnetic particle testing should be assigned top priority for regular rope and weld inspection, due to its rapidity and reliability. Regulations can also include proper consideration to incorporate the advanced NDT methods of infrared and laser scanning into mandatory inspection techniques.

To raise the inspection of the crane to a higher level, it is proposed to use the automated robot MILA 3D for the inspection of the steel parts of the crane structure. The use of this automated robot would make a significant contribution to overcoming the limitations of current methods of inspection of both bridges and other types of cranes. Including NDT tests as part of mandatory preventive and periodic inspections and checks of cranes and their equipment, a significant level of risk and injuries at work would certainly be reduced to the lowest possible level.

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