TECHNICAL NOTE

Review of non-destructive testing methods for physical condition monitoring in the port industry

P.N. Lauritzen¹, J. Reichard¹, S. Ahmed¹, M. Safa^{*2}

¹ Lamar University, Center for Advances in Port Management, Beaumont, USA

² Sam Houston State University, Construction Management, Huntsville, USA

Abstract

Maritime ports are in an asset-intensive industry which requires periodic condition monitoring for infrastructure and equipment. Investments for port physical assets call for more robust lifecycle management, condition monitoring, and maintenance schemes. Port infrastructure and equipment, due to their geographic locations, are under a constant state of deterioration from natural elements such as storms, erosion, and sea spray. The issues that natural elements create, in addition to persistent wear-and-tear, can accelerate the aging process of the port's assets. Inspections utilizing Non-Destructive Testing (NDT) can drastically refine condition monitoring, quality control, and lifecycle management. These improvements have the potential to significantly increase the resilience and readiness of port infrastructure and equipment. This study investigates the current and potential NDT methodologies utilized in the maritime port industry. The objective of this research is to create a comprehensive literature review of following NDT methods: ultrasonic testing (UT), magnetic particle inspection (MPI), rebound hardness testing (RHT), and infrared thermography (IR). The result of this study will be used as a guideline to assist facilities managers in improving current NDT maintenance methods which can be applied to the facility's overall operations.

Keywords

Port infrastructure; Non-Destructive Testing (NDT); Ultrasonic Testing (UT); Magnetic Particle Inspection (MPI); Infrared Thermography (IR)

Received: 15 February 2019; Accepted: 25 June 2019

ISSN: 2630-5771 (online) © 2019 Golden Light Publishing All rights reserved.

1. Introduction and background

Ports face asset-related challenges as a result of neglecting investment in infrastructure condition monitoring. The purpose of this study is to provide industry experts with a guideline that can assist them in finding current and potential NDT methods most appropriate in preventing asset-related challenges. Not preparing for these challenges or letting them prolong without monitoring can become costly as time goes on. A common challenge that a port might face is the deterioration

of infrastructure, which can lead to harming the natural environment. One cause leading to environmental harm is when biological phenomena occur from events such as accidentally discharging emissions, handling liquid bulk through leaky pipelines, etc. [1]. Not only can these events harm the marine environment, but they can also create issues with corporate social responsibility and tarnish the port's image.

Another challenge that ports may face is an increase in maintenance costs. These usually occur

* Corresponding author
Email: mxs167@shsu.edu

when maintenance and repairs for specific structures are avoided. In most cases, it is more cost effective to perform condition monitoring for most structures than to wait until their service lifecycles come to an end (which will result in having to buy a brand-new structure or having a costly repair). A third challenge that ports might face by avoiding condition monitoring is shortened infrastructure lifecycles. This challenge is quite common in a marine setting as the structures endure corrosion caused by natural elements. Due to these environmental factors, such as rising sea levels and sea salt, the lifecycle of these structures can be shortened if not maintained properly [2]. Measures are currently being taken by climate scientists to help project climate change patterns and aid in preparing structure maintenance and testing plans for such events. Climate change is a crucial contributor to accelerating infrastructure corrosion, leading to the structure's shortened life cycle [15]. Applying NDT for condition monitoring to assets that undergo these challenges, such as steel pipelines, can keep stakeholders aware of the asset's state. As a result of this, stakeholders will know when to provide maintenance, replacements, upgrades, etc.

NDT is defined as "the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system" [24]. One can see why NDT is favorable from the definition. The components being tested are not destroyed in any way and will continue to operate after testing is completed, and some can remain in operation while being tested. This benefit can prevent the cost of having to buy new parts for the structure or having to buy a replacement. NDT can also be advantageous as it can supply information for repair data [31]. Such information can help when it comes to quality control and determining if the structure meets certain acceptance or rejection criteria [14]. NDT can be performed at different stages of the structure's construction process to ensure the materials and work meet quality standards.

A few of the many benefits of NDT are product integrity and reliability assurance, manufacturing process control, lower production costs and consistent quality level assurance [24]. Destructive Testing (DT) is usually conducted through harsh operating methods and continues to perform until the asset being tested is destroyed [28]. This type of testing can become costly, which is why infrastructure-rich companies are in search of different testing methods [23]. Another disadvantage of DT is its inefficiency. Resources go to waste through DT since the component being inspected cannot be used after the procedure is completed [29].

The port industry is a significant player in the global economy. TIGER Grants have been popular amongst port infrastructure projects as seventeen percent of these grants in 2010 were awarded explicitly to port infrastructure. Going back to 2007, the AAPA created over 13.3 million jobs in America, \$3.95 trillion in international trade, and over 23.2 billion in U.S. customs duty revenues [19]. American ports have had a competitive advantage due to their affordable transportation costs, but this advantage can become tarnished as the infrastructure continues to deteriorate, which will increase these costs. As of 2016, fifty-nine percent (\$22 billion) of port infrastructure was funded while forty-one percent (\$15 billion) remained unfunded [16].

2. Objective

The objective of this research was to create a comprehensive literature review of following NDT methods: ultrasonic testing (UT), magnetic particle inspection (MPI), rebound hardness testing (RHT), and infrared thermography (IR). The research team investigated the mentioned NDT methods ability to accurately predict a component, or system's, condition throughout its lifecycle within a port facility.

3. Research methodology

During the initial phase of this study, the research team investigated critical port assets which required

monitoring. Building materials that were identified as requiring monitoring were wood, concrete, and metals. Physical assets within a ports' facility which are comprised of wood, concrete and metals are electrical systems, docks, wharves, piers, cranes, motors, piping, etc. After this step, the team compiled research from reliable sources such as academic journals, and reliable websites, such as NDT Resource Center, American Society for Nondestructive Testing, and U.S. Department of Transportation to analyze which NDT methods best fit condition monitoring for each structure. A result/discussion is provided at the end of this review along with the conclusion of this project.

4. Research findings

4.1. Ultrasonic testing

Ultrasonic Testing (UT) is popular due to its ability to detect and evaluate flaws on the component being tested. UT first came to light before WWII, when sonar concepts were being applied in the medical field. Sonar techniques were later used for warfare for metal detection. After the war, Japan aimed its focus back to using ultrasound for medical purposes such as cancer detection and monitoring. The United States started to gain an interest in ultrasound towards the 1950s for medical implementation as well. UT can deliver data by providing readings of deformations and vibrations of materials, which are known as acoustics. A result of the component's condition is achieved by reading wave patterns performed by atoms through acoustics and UT [17]. UT is performed by using electronic transducers that transmit high-frequency sound waves through the material being tested. The waves that are sent back to the transducers appear on an attached screen monitor to reveal data concerning the condition of the material. A few of the many characteristics that can be discovered using UT are cracks, weld grooves, and material thickness.

4.1.1. Accuracy of UT

Using commercial UT technology, wavelength measurement accuracies of $\pm 0.0001\text{mm}$ have

been recorded. On average, UT results are recorded on accuracies of $\pm 0.025\text{mm}$ on common infrastructure materials. Variables such as surface condition, the accuracy of UT instrument calibration, and many others can determine the accuracy of the results [8]. Therefore, it is essential to take these variables into account when performing UT [30]. The end of this section will provide an overview of which port key-components UT can be applied for condition monitoring to ensure reliable results. A recent study performed at Bristol University was done to gather data on UT accuracy using the Total Focusing Method for the first inspection of the study described below (Table 1).

The lengths of defects A, B, C, and D had differences in measurements of -2mm , 17mm , 0.1mm , and -0.5mm , respectively. Defect B had a considerable variation since this defect is a buried 1.49mm vertical rough crack, which is commonly difficult to detect since it is a very tight gap. Gap tightness can lead to ultrasonic reflection being reduced in some regions of the defect. At the end of this study, it was concluded that UT performed on these specimens provided good, accurate results in general [30]. Due to successful UT implementation on metal materials, UT is recommended to be used on port key components such as bridges and conveyor belts. UT can also be utilized on concrete and wood structures, but for the sake of accuracy, it is mainly recommended for metal objects.

4.2. Magnetic particle inspection

The earliest recognized application of magnetism to inspect an object took place in 1868. It was used for checking cannon barrels for defects by magnetizing the barrel and then sliding a magnetic compass along the barrel's length. The defects were able to be located in the barrels by monitoring the needle of the compass by the inspectors. This procedure was a type of NDT application though the term was not customarily used until sometime after World War I.

Table 1. 4419-02 defect size results

Specimen ID	Defect Lengths (mm)			Defect Heights (mm)		
	Intended	Actual	Difference	Intended	Actual	Difference
A	23	21	-2	4.9	5.5	0.6
B	10	27	17	2.3	7.5	5.2
C	10.1	10	0.1	2.5	2.2	-0.3
D	21.5	21	-0.5	5.4	5.5	0.1

In the early 1920s, William Hoke first recognized that magnetic particles (dyed metal shavings) could be used with magnetism as a method for locating defects. It was found that a surface or subsurface defect in a magnetized material caused the magnetic field to deform and stretch out beyond the part. Hoke noticed that the metallic grindings from hard steel parts held by a magnetic chuck shaped patterns on the surface of the parts which correlated with the cracks in the surface. Applying a fine ferromagnetic powder to the parts caused a collection of powder over defects and framed a noticeable sign. Using this concept one of the first Electro-Magnetic Steel Testing Device (MPI) was built by the Equipment and Engineering Company Ltd. (ECO) of Strand, England in 1826. In the mid-1930s, magnetic particle inspection (MPI) was rapidly substituting the oil-and-whiting technique, which was a primary form of the fluid penetrant check, as the preferred technique by the railroad sector [18]. This technique was applied to inspect steam engine boilers, wheels, axles, and tracks. Presently, the MPI inspection technique is utilized significantly to check for defects in an expansive assortment of manufactured materials and components. MPI is utilized to inspect materials, for instance, steel bar stock for creases and other defects before investing machine time during component manufacturing [18].

4.2.1. Accuracy of MPI

Most NDT methods have been primarily concerned with the size of the smallest crack that can be detected and measured. Even though this is of extraordinary significance, the entire area of crack measuring, both length, and depth, turns out to be somewhat questionable if the matter of estimating

reliability is not also considered [32,33,34]. To investigate the effect of crack closures on the reliability of NDT calculations of crack measure, tests were performed on mild steel plate samples each having a fatigue crack. The extent of crack opening or closure is controlled using a specially designed four-point bending rig. Four NDT techniques were studied: dye penetrant testing, magnetic particle inspection (MPI), AC field measurement (ACFM), and an ultrasonic technique using Rayleigh waves. A success/failure standard for the reliability of sizing was adopted and both the length and depth data were analyzed as per this condition. For every positive load while crack opening, the dye penetrant testing was found to have a 100% length estimating reliability based on the chosen success/failure criterion. Then again, with increasing crack closure the reliability of length estimating decreased consistently until a load value was reached at which the crack could not even be detected (a zero percent length sizing reliability). MPI and ACFM have a crack length estimating the reliability of one hundred percent over the whole load run considered. An adjustable-yoke electromagnet was used along with Ardrex fluorescent magnetic ink to perform the MPI tests. The inspection was carried out under UV light; the length of any indications being measured using a steel rule. The crack length measuring reliability attributes shown by the ultrasonic Rayleigh-wave testing method was like that for the dye penetrant testing, the main genuine contrast being that the drop-off in dependability began at a small positive load value for the ultrasonic procedure. When interpreting the results, tests were applied to fatigue cracks in medium-strength mild steel plate specimens and that the statistical results are based on a sample size of fifteen. The work aimed to

produce, within a specified period, a quantitative idea as to the effect of crack closure on NDT sizing reliability. The results of the study demonstrated that both magnetic particle inspection (MPI) and air conditioning field measurement (ACFM) could detect and measure closed cracks but dye penetrant testing and the ultrasonic Rayleigh-wave method cannot find very closed cracks. When opening a crack, all of the techniques used in the study were able to predict the crack length to within $\pm 10\%$ variation of the actual value with the reliability of one hundred percent. On closing the crack though, only the MPI and ACFM techniques were able to repeat the one hundred percent reliability characteristic, which is a reliable indicator of the accuracy of the techniques as well [7]. The MPI technique applies to all underwater metal components of the ship structure which can be strongly magnetized; such as ferritic steels and irons. Underwater MPI is utilized principally as a quality assurance tool to help underwater welding on ship structures.

4.3. Rebound hardness test

The rebound hardness test (RHT) methods are essential when it comes to researching certain attributes of new material and ensuring that a material meets particular hardness standards [10]. Hardness testing dates back approximately three-hundred years. The well-known scratch testing method has been the pioneer of hardness testing, dating back to the year 1722. A century later in 1822, scratch testing became more sophisticated by scratching the material with a diamond and measuring the width of the scratch left on the material to determine the hardness, which became known as the famed Mohs scale. Since then, more advanced methods of the Mohs scale have been developed [3]. The first NDT hardness test was developed in Germany in 1934, which used a very similar concept to the Leeb Hammer test as it included a ball indentation function as well [22]. Forwarding to 1975, the Leeb Hammer Test was finally developed by Leeb and Brandestini and has been improving ever since, thanks to the rapid advancement of technology [6]. The Leeb Hardness

Test is performed with a rebound hammer which consists of a window and a scale that show the hardness results, a mass that may consist of different materials such as a carbide ball depending on the hammer being used, an impact spring, and a plunger. The procedure of the hammer test starts with the plunger being pressed against the material being tested. After the plunger is released, the impact spring releases the mass powered with constant energy. The mass impacts the material being tested then rebounds, providing a result on the window and scale [25]. Depending on the material being tested, the rebound index reading can assist in determining the required hardness for that specific material.

4.3.1. Accuracy of RHT

When it comes to performing hardness testing with the rebound hammer, the accuracy of the results can vary depending on the materials being tested due to their properties. For example, accuracies of the hammer test on metal forms have ranged from five to twenty-five percent higher than when tested on wooden forms [13]. When hardness testing is performed on concrete structures, studies have shown that there are accuracy variations of fifteen to twenty percent due to the many limitations of the test [11]. The end of this section will provide an overview of which port key-components RHT can be applied for condition monitoring to ensure satisfactory results. A study published in 2014 under The International Journal of Advances in Agricultural & Environmental Engineering was performed to observe the reliability of RHT on concrete when exposed to different conditions. One hundred eight samples of 150mm concrete cubes, grouped into three, were each studied under the following conditions: one group exposed to cycles of alternate drying and wetting in brackish water, the second exposed to continuous immersion in brackish water, and the third (controlled) exposed in normal room conditions. After the wet samples were set out to dry for twenty-four hours, sixteen rebound readings were performed on each specimen; each hammer hit spaced at least 25mm. After RHT was performed, the specimens were

loaded to failure on a compression machine to determine their true hardness. Statistical t-testing and linear regression models were created to analyze the test results: For the samples exposed to alternate drying and wetting cycles of brackish water, the accuracy of RHT was underestimated by nine percent from the actual concrete strength. For samples that were continuously emerged in brackish water, the accuracy of RHT was underestimated by thirteen percent. For samples that were exposed to normal room conditions, accuracy was underestimated by seventeen percent. Overall, the study showed that RHT is more reliable when testing wet concrete strength, but the instrument must be calibrated correctly, and a rebound correlation curve should be developed before performing hardness testing [21]. As we learned from the study explained in this section, RHT can be most beneficial to port key components such as jetties and caissons due to their constant exposure to seawater. RHT is a unique method due to its ability to provide condition monitoring data for key components submerged under water.

4.4. Infrared thermography

Infrared Thermography (IR), is a powerful tool used for preventative maintenance, predictive maintenance, and troubleshooting. Its study can be broken down into two separate times. In 1800, Sir William Herschel, who was the royal astronomer of King George III, is said to be the founder of infrared energy. Hershel believed different colors would transmit different levels of energy and conducted an experiment to test his hypothesis [4]. He passed sunlight through a prism and measured the temperatures of the various colors and found he was correct. Though, long before Herschel, infrared energy was hypothesized by Titus Lucretius Carus, a Roman poet and philosopher. Then, in 1696 an Italian observer named Della Porta felt the heat from a candle when it was placed at the forefront of a silver bowl. Thanks to the studies of Planck, Einstein, Kirchhoff, and others, the second birth of thermal sciences began in 1900. During WWI and WWII, IR technology improved rapidly for the detection of aircraft and ships, which also

contributed to NDT implementation. IR was first used for NDT as a process to analyze hot rolled metal in 1935. During the 1960s, IR began being utilized commercially for electrical installations, radio and electronic equipment, and buildings [9]. IR can be used to detect defects such as cracks and splits in materials, examine the thermal stress that is placed on a machine, monitor the friction surfaces of machines, and inspect electrical components [27]. This method can even be used to locate obstructions in piping. Before a component within a system fails, there is usually a rise in temperature above normal operating parameters. IR Thermography works by utilizing a camera that can detect heat signatures in infrared wavelengths which are not visible to the human eye and can be categorized in two ways: passive or active [26] What makes IR so attractive is that it is a non-contact and non-intrusive NDT method that allows the user to see potential failures before they take place.

4.4.1. Accuracy of IR

The accuracy of IR Thermography can vary significantly on the quality of the equipment used, the equipment's intended use, the level of training of user, the material being tested, and the ambient air temperature. Different cameras are built to different specifications, and the user will have to determine the appropriate camera for the application. One such use is thermal imaging attachments for smartphones. The smartphone attachment is designed primarily for detecting heat loss from piping or building inspection, so the device will not be as accurate as a high-end thermal imaging camera.

A food processing and packaging company implemented a two-year study utilizing IR thermography for NDT. For the first year of the study, the research team conducting the investigation developed a pilot program. During the pilot program, equipment was identified to be investigated based on the World Class Manufacturing strategy, which the food processing and packaging company already had implemented. Electrical equipment was primarily studied such as

“transformers, switchgear, industrial fuses, contactors, DC motors, and other equipment” [27]. The research team conducting the investigation recorded the initial temperatures of seventy measuring points. The components studied were under normal load and operating conditions.

The guidelines for condition monitoring and its proposed actions are reported in Table 2 shown below.

Without prior measurements on the components studied, the first-year measurements were on the side of caution and were marked at a higher risk. During the second year of the investigation, the research team conducting the investigation of re-recorded temperatures and reduced the severity of the results. At the end of the two-year study, it was concluded that the IR condition monitoring reduced the number of potential failures by ninety percent and the cost associated with breakdowns were also reduced. Unfortunately, the company that implemented the investigation considered the cost reduction data confidential information, and therefore, it is not available [27]. Port key components ranging from shore power connections to plumbing are a few of the many components that can be benefited from utilizing IR for condition monitoring. IR is unique in the sense that it can provide condition monitoring data for not only wooden, metal, or concrete components, but on electrical components as well, which is difficult to obtain using other NDT methods.

5. Research findings

The contribution of this study to the port industry in Table 3 shown below. The matrix lists structures and their material makeup within the port facilities. The components in the first column on the left describe the specific material component part of the port structures listed in the top row; For example, The metal parts of the bridge can be tested with UT, MPI, RHT, and IR while the wooden parts of the bridge should only be tested using UT and IR. Our research team chose UT, MPI, RHT, and IR due to the material makeup of many of the components located in ports. These NDT methods are the most

common methods for condition monitoring. Facilities managers must ultimately choose the proper NDT method by considering the following variables (which were taken into consideration when selecting the methods in the matrix): material composition, environmental conditions, component location, the accuracy of testing equipment, and competency of the NDT technician.

6. Limitations

Currently, there is limited condition monitoring data available from within the port industry. Therefore, the research team applied data from other industries that employ the same building materials, in similar conditions as the port industry. There are many other NDT methods available to help assess conditions, but our research team chose UT, MPI, RHT, and IR due to the technology being readily available and the proven accuracy to detect defects within a material. As NDT and condition monitoring technology advances, the accuracy of the NDT methods and the data collection process will improve prompting further research within this topic.

7. Conclusion

As maritime ports continue to improve on their business models, the need for condition monitoring will continue to grow. In this study, the key NDT technologies used in the port industry with their limitations have been investigated. The review shows that NDT plays an important role in the condition assessment of key port infrastructures. The data that the research team compiled from other industries can offer insight to port facility managers in tracking the condition of infrastructure. As stated in the analysis, the NDT methods that the research team selected allow for the monitoring of bridges, caissons, conveyor belts, docks, gantry cranes, jetties, motors, piers, piles, piping, rail, shore power connections, substations, and wharves. As mentioned before, other NDT technology is available to monitor infrastructure and further research will be required to help port facility managers track their infrastructure.

Table 2. Guidelines for condition monitoring and proposed actions [27]

ΔT (°F)	Description of condition and recommendations for similar components under similar loading conditions
1-16	Normal : Continue regular condition monitoring schedule
16-36	Warning : Equipment should be scheduled for maintenance during the next maintenance period, and the user should increase condition monitoring.
>36	Danger : Equipment requires immediate repair.

Table 3. NDT methods recommended for specific port components.

	Bridges	Caissons	Conveyer Belts	Docks	Gantry Cranes	Jetties	Motors	Piers	Piling	Piping	Rail	Shore Power Connections	Substations	Wharves
Metal	UT MPI RHT IR	---	UT MPI RHT IR	UT MPI RHT	UT MPI RHT IR	RHT	---	---	UT MPI RHT	UT MPI RHT IR	UT PI RHT IR	---	---	---
Concrete	RHT IR	RHT IR	---	IR	---	IR RHT	---	IR	RHT IR	RHT IR	---	---	---	---
Electric	UT MPI IR	---	UT MPI IR	---	UT MPI IR	---	MPI IR	---	---	---	---	UT MPI IR	UT MPI IR	---
Wood	IR	---	---	IR	---	RHT	---	IR	IR	---	---	---	---	IR

References

- [1] ABP Research. Good Practice Guidelines for Ports and Harbours Operating within or Near UK European Marine Sites. UK Marine SACs Project, UK, 1999.
- [2] Almeida B, Mostafavi A (2016) Resilience of infrastructure systems to sea-level rise in coastal areas: impacts, adaptation measures, and implementation challenges. *Sustainability* 8(11): 1115; <https://doi.org/10.3390/su8111115>.
- [3] AZoM. Hardness testing—a brief history. AZO Materials 2018. <https://www.azom.com/article.aspx?ArticleID=15121> (accessed October 31, 2018)
- [4] BioSmart Solutions. History of infrared & infrared technology. BioSmart Technologies 2012. <http://biosmartsolutions.com/shop/buyers-guide/technology/history-of-infrared-technology/> (accessed September 5, 2018)
- [5] Blitz J. *Electrical and Magnetic Methods of Non-Destructive Testing*, Springer, 1997.
- [6] Cimetrix. Leeb (rebound) 2018. https://www.leebhardnesstesters.com/portable_hardness_testers/leeb_hardness_testers (accessed November 8, 2018)
- [7] Clark R, Dover WD, Bond LJ (1987). The effect of crack closure on the reliability of NDT predictions of crack size. *NDT International*, 20(5): 269-275.
- [8] Explore the World of Piping. Non Destructive Testing-Ultrasonic Testing 2018. http://www.wermac.org/others/ndt_ut.html (accessed September 9, 2018)
- [9] FLIR. The Global Leader in the Design, Manufacture, and Marketing of Thermal Imaging Infrared Cameras 2018. <https://www.flir.com/about/company-history/> (accessed October 29, 2018)
- [10] Frank S. (2001). Innovations in portable hardness testing. *The e-Journal of Nondestructive Testing & Ultrasonics* 6(9): 1-4.
- [11] Gharpedia. Uses of rebound hammer test and its limitations 2018. <https://gharpedia.com/uses-rebound-hammer-test-limitations/> (accessed July 15, 2018)

- [12] Hannachi S, Guetteche N (2012). Application of the combined method for evaluating the compressive strength of concrete on site. *Open Journal of Civil Engineering* 2: 16-21.
- [13] Hannachi S, Guetteche N. Review of the Rebound Hammer Method Estimating Concrete Compressive Strength on Site. *International Conference on Architecture and Civil Engineering*, 25-26 December 2014, Dubai.
- [14] Jesse Garant Metrology Center. NDT Services 2018. <https://jgarantmc.com/ndt-services/> (accessed November 16, 2018)
- [15] Kong D, Setunge S, Molyneaux T, Zhang G, Law D (2012). Australian seaport infrastructure resilience to climate change. *Applied Mechanics and Materials* 238: 350-357.
- [16] Navales E (2016). Paying the Price. *Right of Way Magazine* 63(4): 18-23.
- [17] NDT Resource Center. History of Ultrasonics 2014. <https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/history.htm>
- [18] NDT Resource Center. (2014). History of Magnetic Particle Inspection 2014. <https://www.nde-ed.org/EducationResources/CommunityCollege/MagParticle/Introduction/history.htm>
- [19] Pulidindi J. Port infrastructure: transportation for the economy 2010. <https://www.nlc.org/article/port-infrastructure-transportation-for-the-economy>.
- [20] Rizzo, P. (2014). Sensing solutions for assessing and monitoring underwater systems. *Sensor Technologies for Civil Infrastructures* 2: 525-549.
- [21] Sanchez K, Tarranza N (2014). Reliability of rebound hammer test in concrete compressive strength estimation. *Int'l Journal of Advances in Agricultural & Environmental Engineering* 1(2): 198-202.
- [22] Szilagyi K. *Rebound Surface Hardness and Related Properties of Concrete*. Budapest, 2013.
- [23] TeTechs. The Cost of Destruction 2017. <http://tetechs.com/2017/01/cost-of-destruction/> (accessed November 1, 2018)
- [24] The American Society for Nondestructive Testing. Discover Nondestructive Testing (NDT) 2018. https://www.asnt.org/MinorSiteSections/AboutASNT/What_is_NDT.aspx (accessed November 3, 2018)
- [25] The Constructor. Rebound Hammer Test on Concrete – Principle, Procedure, Advantages & Disadvantages 2018. <https://theconstructor.org/concrete/rebound-hammer-test-concrete-ndt/2837/> (accessed October 22, 2018)
- [26] Theodorakeas P. Thermal NDT & E of Composites. 2011. http://www.enea.it/it/seguici/events/compair-28giu11/NTUA_Kauppinen.pdf (accessed November 10, 2018)
- [27] Todorović PM, Gordić D R, Babić MJ, Jeremić BM, Demichela M, Mačuzić ID (2013). An implementation of infrared thermography in maintenance plans within a world-class manufacturing strategy. *Thermal Science* 17(4): 977-987.
- [28] Tutorialspoint. What is Destructive Testing? 2018. https://www.tutorialspoint.com/software_testing_dictionary/destructive_testing.htm (accessed October 20, 2018)
- [29] Verichek Tech Services. (2017, September 15). Destructive vs non-destructive metal testing? 2017. <https://verichek.net/destructive-vs-non-destructive-metal-testing.html> (accessed November 3, 2018)
- [30] Wedge S, Carter L, Rogerson A, Zhang J, Drinkwater B. Defect detection and sizing trials using the total focusing method and scattering coefficient matrix with a linear phased array. 10th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, 1-3 October 2013, Cannes, France.
- [31] Worldspec. About NDT 2018. <https://www.worldspec.org/about-ndt/> (Sep 24, 2018).
- [32] Safa M, Sabet A, Ghahremani K, Haas C, Walbridge S (2015). Rail corrosion forensics using 3D imaging and finite element analysis. *International Journal of Rail Transportation* 3(3): 164-178.
- [33] Ghahremani K, Safa M, Yeung J, Walbridge S, Haas C, Dubois S (2015). Quality assurance for high-frequency mechanical impact (HFMI) treatment of welds using handheld 3D laser scanning technology. *Welding in the World* 59(3): 391-400.
- [34] Safa M, Nahangi M, Shahi A, Haas CT. An integrated quality management system for piping fabrication using 3D laser scanning and photogrammetry. *International Symposium on Automation and Robotics in Construction*, 11-15 August 2013, Montreal, Canada.