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Qualifying existing reinforced concrete (RC) structures using non-destructive testing methods

ABSTRACT

Qualifying and maintenance of reinforced concrete structures to extend their lifetime and create reuse opportunities by non-invasive techniques have been highly regarded by researchers from different disciplines since condition assessment of such structures is not only a complex process, but costly and time-consuming. In this paper a literature review on the most recent development of non-destructive testing (NDT) methods along with interviews with experts have been conducted to highlight the advancements, NDT trend, and research gaps in this field. Furthermore, a futuristic vision of NDT has been presented considering its trend towards the last generation of non-destructive evaluation (NDE), NDE 5.0. The outcome shows that implementation of UAVs, AI, and combination of different methods significantly improve the results. However, algorithms need to be developed and AI models should be published for transparency. Integration of NDT results and data formats have been identified as research gaps, which should be considered regarding the future vision. Provided that the requirements are met, condition assessment of RC structures will be revolutionized by NDE 5.0.

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Keywords: Reinforced Concrete, Non-Destructive Testing, Qualifying, Non-Destructive Evaluation, Condition Assessment, Structural Health Monitoring

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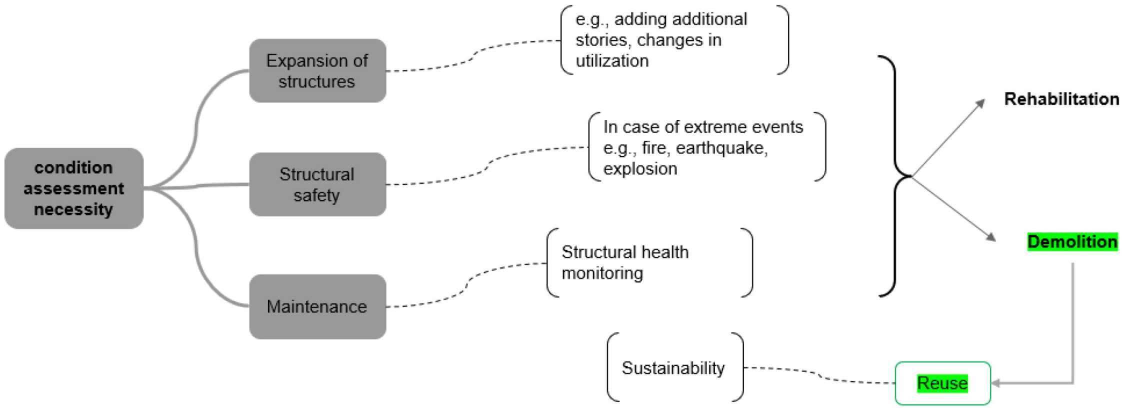

Fig. 1 Three main categories regarding condition assessment necessities

7. Introduction

Qualifying is too general a topic as we have to deal with different types of widely used materials, namely steel, concrete and timber, which have their own design codes and maintenance standards. Therefore, in this paper we have solely focused on Reinforced Concrete (RC) structures in order to undertake a literature review on the most recent developments in Non-Destructive Testing (NDT) methods and highlight the NDT trend as well as its future vision considering the essential requirements and benefits. Nevertheless, it should be noted that NDT is so complex a topic as it is an interdisciplinary field which encompasses many disciplines such as physics, chemistry, material science, computer technology and communication technology [1].

The reasons why we need to conduct a condition assessment of structures using NDT have been divided into three main categories. Expansion of existing structures is one of them. In order to ensure that an existing structure is capable of satisfying structural requirements so that it can be extended, it should be qualified whether an expansion would be allowed. Adding an extra story on top of a building is an example.

Furthermore, in case of extreme events such as an earthquake, an explosion or fire, structural safety has to be evaluated to confirm that the structure would be able to bear the loads regarding the extent of the damage.

Maintenance of existing structures is also one of the qualifying necessities. Considering the total number of existing bridges for instance in Germany, around 140,000 [2], it is evident that maintaining such structures is crucial in terms of sustainability and also construction costs. Therefore, health monitoring of structures plays a key role in extending lifetime of structures, which in long term saves significant money and material.

After assessing the condition of an existing structure, structural engineers end up having to decide whether the structure meets the requirements, needs to be strengthened or demolished. In case of demolition, splendid reuse opportunities could be created if suitable, non-invasive methods are at our disposal to efficiently evaluate the condition of the elements. Fig. 1 illustrates the main points.

1.1 Testing methods

In principle, material testing methods can be divided into two main categories, namely Destructive Testing (DT) and Non-Destructive Testing (NDT) methods. DT is performed to determine the mechanical and chemical properties of the material. Although DT is reliable and useful for design and evaluation purposes, it's not only expensive and time-consuming, but the tested specimen is destroyed [3].

Quality assurance of concrete has traditionally been performed mostly by visual inspection and collecting samples of concrete to conduct standard tests on hardened specimens, however, such

NDT method	Application	Advantages	Disadvantages
Acoustic Emission (AE)	○ Cracks ○ Corrosion of reinforcement	Simple operation	○ Vulnerable to electromechanical noise ○ Sensitive to materials
Infrared Thermography (IRT)	Cracks	Test different Materials	○ Limited measurement depth ○ Time-consuming
Ground Penetration Radar (GPR)	○ Voids ○ Corrosion of reinforcement	○ Fast measurement speed ○ Easy operation	Susceptible to metals

Table1. Three examples of NDT methods

approaches do not provide information about "in-place properties of concrete" while NDT methods alleviate the problem [4, pp. 2].

ACI228.2R-13 [4, pp. 2] states that NDT methods provide information such as location of cracking, delamination and debonding, location and size of steel reinforcement, corrosion of reinforcement, and strength of concrete.

Although there are a number of different NDT methods, the Infrared Method (IR or IRT) has been briefly explained here. Its working principle is based on measuring the temperature changes on structures' surface as a result of compression or tension. As concrete structures with debonding or delamination emit infra-red radiation, "this

method uses specialized scanning cameras to capture the emitted heat at any temperature and convert the data into thermal images for further analysis" [5].

Zheng et al. [1] have conducted a literature review on seven NDT methods and summarized the advantages, disadvantages, and application of those methods. Table 1, which has been extracted from [1], shows three methods, by way of illustration in this paper.

Obviously, the working principle, application, advantages, and disadvantages of NDT methods are crucial factors in selection of testing methods. Additionally, "*the economy and environmental protection*" of such methods should be taken into account [1]. As mentioned before, NDT is an interdisciplinary field, therefore, development of NDT methods is dependent on the development of those disciplines.

According to ACI228.2R-13 [4], NDT methods are being increasingly applied for condition assessment of RC structures because of:

- Improvements in technology in terms of software and hardware for data collection and analysis.
- Economic advantages of investigating large volume of concrete.
- High speed of operation.

Furthermore, the ability to assess complex structures which could be created regarding advancements in Additive Manufacturing (AM) is also an important factor.

Considering all the mentioned points, the main research questions in this paper have been formulated as follows:

- How can existing RC structures be qualified more accurately using NDT methods to enhance the lifetime of buildings and create efficient reuse opportunities?
- What would be the future vision of condition assessment of RC structures by NDT methods?

8. Methodology

In order to provide answers to these questions, a literature review as well as interviews with experts [6,7] in the industry have been conducted.

8.1 Literature Review

We have focused on the literature published no more than two years ago from the date of final colloquium in Research

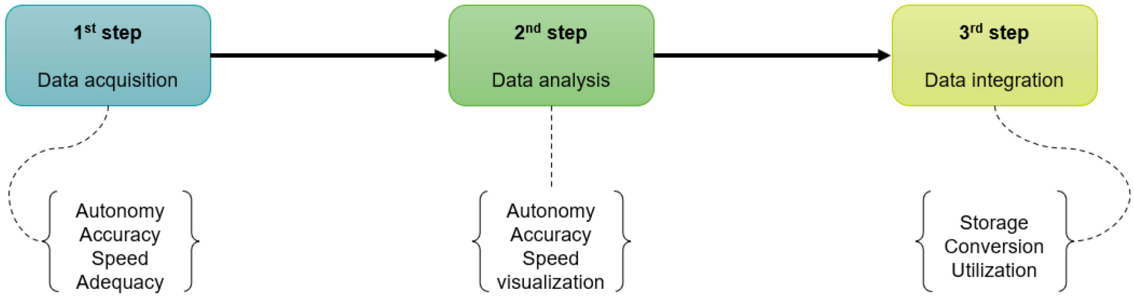

Fig.2 NDE process in three steps

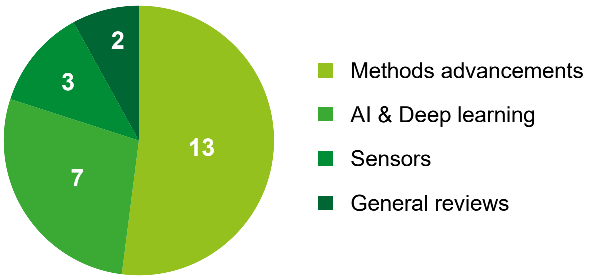

Fig. 3. Distribution of the reviewed papers according to their main topic.

Driven Project (RDP) course at RWTH, 01.02.2023. In this paper the Non-Destructive Evaluation (NDE) process has been divided into three main steps shown in Fig. 2 so that the results and insights can be categorized accordingly.

The field of NDT for reinforced concrete is very extensive, it is necessary to narrow down the scientific papers related to this topic. A search on *Google Scholar* lists about 42.500 articles, that contain the words “ndt”, “testing” and “concrete” [8]. As we have decided to focus on the latest trends, we searched for papers published in the last two years. Two recent reviews from 2022 and 2021 serve as baseline of the state of the art in NDT developments. All papers that have been read were checked for reference in these reviews and only when there hasn’t been written anything included in this paper. After this procedure 22 articles were reviewed, and the findings concluded in the following paragraphs. In Fig. 3. the distribution of topics of the reviewed papers can be found.

8.2 Current reviews

The first review by Kot et al. covers developments in the methods of Sweep frequency technique, ground penetrating radar (GPR), infrared technique (IR), fiber optic sensors (FOS), camera-based techniques, laser scanners, acoustic emission (AE) and ultrasonic techniques [5]. I n particular, the authors wish to highlight the use of sensors in NDT methods, emphasizing the arguments that sensors minimize monitoring costs and sudden failure accidents.

In the second review, advancements in NDT-methods for evaluation of concrete in bridge engineering are summarized [1]. Seven methods were examined and compared with application examples and limitations. The paper concludes with recommendations for further research including the following topics: Detection technology combined with unmanned aerial vehicles (UAV), wireless remote sensing and wireless sensor technology, machine learning (ML) and deep learning (DL).

3. Outcome

The paper of Solla et al. gives a comprehensive overview of different applications of GPR in the field of construction [9]. It highlights the capability of GPR to give good results in thickness and moisture detection of concrete and the advancements in recent years regarding the interpretation of measuring data using new algorithms based on artificial intelligence (AI). Also, it highlights the potential of combining GPR with other NDT methods and mount these to UAVs.

Another paper that deals with the GPR method is from 2022 by Lombardi et al. and focuses on a more widespread analysis of GPR in different practices [10]. It’s worth noticing that the findings were in general congruent with the previous paper. The researchers underline the need for a more encompassing framework when it comes to data acquisition. This is especially valid for geophysical problems, but it could also be applied to construction related tasks.

In their paper on structural health monitoring (SHM) using computer vision and UAVs, Sabato et. al. used Computer Vison techniques to refine Infrared (IR) images, so that they were able to detect subsurface cracks in pavements [11]. This could be achieved by applying the Sparse-principal component thermography.

In an experimental study, Deba Datta Mandal and his colleagues adopted acoustic emission-based techniques to monitor progressive damage mechanisms in reinforced concrete T-beams [12]. The results and parameters of the four-point bending test on three different samples were then used and implemented in different algorithms including machine learning based ones like Support Vector regression. An unsupervised ML learning approach based on the k-means method sorted the data into according to different types of damage.

Sajid and Chouinard provide a review on the Impulse response method [13]. The paper examines the state of art and point out possible directions for future research. Advanced data analysis methods as well as numerical simulations and a better understanding of the boundaries of the Impulse response method, are the suggested next steps by the researchers.

The same technology is treated in another research published by Sajid et al. The proposal is an algorithm to automatically locate and rank defects in concrete plates using the Impulse response measurement data [14]. The researchers programmed an unsupervised algorithm based on statistical pattern recognition that doesn’t need any beforehand calibration with the tested element. Two concrete plates were used as test objects to demonstrate the superiority of the algorithm against state of the practices.

Santos et al. propose a technique of image capturing with UAVs to detect exposed rebars on concrete structures [15]. The georeferenced images are then run through a deep learning algorithm that is based on the AlexNet CNN. Two case studies on large concrete structures were made and the accuracy of 99.1% from the training process could be validated under real world conditions.

Terrestrial laser scanning (TLS) is another method working with visual appearance of structures as base. In their review Wu et al. analysed applications of TLS in the AEC Industry. Research that has been done regarding combination of TLS with IRT is mentioned as well as the rising interest in deformation measurement and monitoring [16]. The authors point out the need for further research in order to improve data processing, automatization, and adaption of artificial intelligence tools.

In their recent study Mahmoudi et al. set up a study to determine the most efficient machine learning algorithm to classify damage in concrete shear wall buildings [17]. After they found out, that the K-Nearest Neighbor (KNN) algorithm was the most compatible, they build a framework and tested it against three benchmark buildings and in the end could verify the efficiency of the approach.

Another article that has been published in 2022 tackles the importance of identifying data anomalies in SHM data sets. Zhang et al. developed a new approach combining CNN and statistic features which yields in faster and more accurate results and is able to detect up to 94.26% of anomalies [18].

Taheri et al. created an overview which machine learning algorithms were used on data of different NDT methods [19]. In addition, the potential of artificially generated training data for ML is mentioned and concluded that AI/ ML based techniques can double the precision of defect detections.

The same topic gets covered in a survey by Lavadiya et al., where the research is aimed at various Deep learning models for NDT evaluation of concrete bridge decks [20]. It was found that the novel one-dimensional convolutional neural networks (1DCNN) can predict better results from IE signals then conventional CNNs. Furthermore, the authors underline the need for reliable datasets. More measurements from different structural buildings means more data to test the proposed algorithms against, resulting in more resilient algorithms.

The paper by Deng et al. contributes to the application of DL to NDT data. The proposal trained a customized Mask R-CNN on a set of Infrared Thermography (IT) images [21]. The overall average relative error of the model is 0.7%.

Kapteina et al. published an article in which they examined the assessment and restoration of chloride contaminated building components using Laser-induced breakdown spectroscopy [22]. Not only provides the LIBS method a fast approach to measure the chloride content in concrete structures, it can also be used to review the effectiveness of treatments. However, it is only seen as an additional technique to supplement renown methods.

An overview of corrosion monitoring techniques for rebars in concrete structures by Fan et al. compares different types of sensor systems and sort them into application due to the stages of rebar corrosion [23]. The researchers state various problems when it comes to application of sensors in RC structures. That is, for example the short lifespan of sensors compared to that of the RC buildings as well as the difficulty of retrofit sensors in existing buildings. A maintenance management system is proposed to help choosing the right sensor and find the best location for positioning.

Berrocal et al. worked on embedded sensor systems in reinforced concrete. Two distributed optical fibre sensors (DOFS), one with additional protection and one without, were put into an RC beam and tested for crack detection [24]. The measured data was then put into a function and transferred into a contour plot describing the crack pattern.

Another work that tested sensors in RC structures, evaluated the sensitivity of ultrasonic sensors. Chakraborty et al. validated the sensors and signal processing on 3 different concrete structures [25]. Also, the authors found out that the optimal distance to place the sensors lays about 1.5 meters apart.

To retrieve the best predictions for the compressive strength of self-compacting concrete, Beskopylny et al. compared different ML based algorithms. The result showed that all models had a mean absolute percentage error between 6.15 and 7.89%, with the k-nearest-neighbours as the most favourable one [26]. These models could be implemented easily within the construction industry, in addition the data gained from industry could be accumulated and provided for further research.

A paper on ultrasonic wave technology was published by Diewald et al. [27]. Their aim was to analyse how external loads influence the ultrasonic waves inside a concrete specimen. Due to implemented experiments, correlation coefficients could be created giving a more comprehensive view on the topic.

8.3 Expert interviews

Two interviews with experts, that were or are working in the field of NDT testing were held [6,7]. The goal of the interviews was to identify the state of the art in practical applications, as well as trends and challenges. The following conclusions were drawn from the interviews.

- NDT methods for estimation of concrete strength lack accuracy and can often only serve as a supporting method for assessing structures.
- Parking garages are a good example of where NDT methods in existing buildings come into operation.
- Importance of viewing data sets before training on ML / DL algorithms.
- Standardized qualification for engineers doing NDT testing should be implemented.
- End users need to be trained to understand the advantages and limitations of NDT.
- Emphasis on correct calibration that needs to be on site.
- Standards for permanent sensors in RC structures

9. Future vision

In this section, how NDT methods and the underlying procedure could look like in the future has been covered. These assumptions are made from the base of the reviewed literature and the expert interviews. For comprehensibility the proposed visions are put in the context of an example project. A parking garage has to deal a lot with moving forces and polluted substances and therefore the SHM for this kind of building is of great interest.

The easiest and fastest way to assess structures is to use visual inspections. As mentioned in the literature review, there is research that covers this area. Currently the main focus lies in mounting sensors like IR onto UAVs or using computer vision algorithms on pictures taken by a drone. Image acquisition can be extended even further. Civilians could use their smartphone to photograph visible defects in concrete buildings and submit the localized pictures through an app. If a certain number of people provide pictures, weak spots can be easily identified, and further measures can be taken. Surveillance cameras that are equipped with Lidar technology can help to measure long time deformations or sudden failures. In the future a lot of cars will also have this technology and therefore could also capture images in the parking garage.

Sensor systems will also play a major role when we think about how SHM of building will be executed in the future. The focus should lay on a holistic approach for a sensor system that not only evaluates the structure but also the surrounding environment. In the case of the parking garage several sensors could measure temperature, moisture content, vibrations, winds, air quality. Other embedded sensors in concrete could measure cracks, corrosion of rebars or compressive strength. Evaluation and correlation between all sensors could lead to a better understanding of which measures should be taken to have a longer living structure. It's important to develop sensor systems that not only can be built in during the construction process but also be implemented into existing concrete structures. Together with images or in-situ tests, the amount of data will increase significantly and only algorithms can take care of the sampling and sorting procedures. As today a lot of researchers are working to implement various AL/DL algorithms to NDT methods, the future will rely even more on these techniques.

The processes of data acquisition and interpretation need to be supervised by professionals to make sure models get trained properly and the obtained results can be applied to the real structure. These processes can be time consuming, therefore wherever there is a need for measurement or calibration on site, robotic systems should step into place. The data can be implemented in Digital Twins for a comprehensive real time model of the building [28].

This is what NDE 5.0 is striving for: a fully autonomous, self-learning system where human interventions are kept at minimum and actions are performed by robots [29].

The ideal case would be a parking garage that doesn't need to be demolished, through constant structural maintenance. Therefore, it has to be ensured that the conclusions drawn from the measured data are precise.

10. Results & Discussion

In this paper we have undertaken a literature review on the most recent developments in NDT and interviewed experts to highlight the advancements, challenges, and trend of NDT from a futuristic point of view. The findings can be summarized as follows:

- A great deal of research has been conducted into the implementation of DL and ML to improve the data acquisition and analysis processes. Although scientific results show significant improvements, insufficient amounts of data about these models are published and freely accessible. Therefore, it remains unclear whether these models are trained based on artificial defects data, and to what extent such models can be extended to have a comprehensive model which could be applied to different scenarios.
- UAVs are increasingly being employed to investigate RC structures. This could be regarded as a huge step towards increasing speed and accuracy of operation while decreasing time and budget as UAVs can be sent to inspect some areas which are hardly accessible to humans.
- Integration of NDT results could be considered as a research gap as this is a subject to which less attention has been paid. The NDT results could be stored in a cloud and converted into different interoperable formats for further processing. Additionally, such data could be integrated into the digital twin of structures so that defects can be predicted regarding NDE 5.0.
- A novel data acquisition system could be launched so that citizens can take part in the data acquisition and visual

inspection phase. For instance, they can send some pictures of the likely defects and it could be automatically analyzed.

- Coring or other testing methods need to be performed to verify NDT results.
- Training of engineers should also be considered. Civil Engineers should be trained during their studies about NDT methods so that they would have basic knowledge upon graduation.

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