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Diagnosis of Historic Reinforced Concrete Buildings: A Literature Review of Non-Destructive Testing (NDT) Techniques

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Abstract

Non-destructive testing (NDT) techniques are employed by many authors as reliable and effective methodologies to investigate the current conservation state of historic buildings and to follow up its evolution in response to the surrounding environmental changes. This paper briefly reviews the scientific articles dealing with NDT techniques applied to historic reinforced concrete (RC) buildings. To this purpose, 32 articles were selected through the steps of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) flow diagram and critically analysed. It emerges that Acoustic Emission and Ultrasonic techniques, Thermography, Rebound Hammer, and Electromagnetic techniques (e.g., Eddy Current and Ground Penetrating radar) are commonly employed due to their ability to detect damage in RC structures. As a result, the combined use of acoustic and mechanical methods (also known as "SonReb" Rebound Hammer and Ultrasonic Pulse Velocity) is found to be the approach more frequently used in the revised documents. This work allows to guide in the selection of NDT techniques to study the rate of decay, if any, and shows the way towards the development of new early warning approaches and best practices for maintaining historic RC structures.

Keywords: Non-destructive testing; reinforced concrete; historic construction; literature review; PRISMA.

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1. Introduction

Starting from the twentieth century, churches, museums, and warlike buildings have been built with reinforced concrete (RC) due to its good performance in strength and durability. However, RC structures can be damaged by climate-induced deterioration factors due to extreme environmental events as well as to the daily exposure to external climate conditions (Ayinde et al. (2019), Boccacci et al. (2023)). Evidence of degradation due to use and time typically reveals the necessity to enhance an existing building's life expectancy in surviving weathering action, chemical attack, embedded chemicals, alkali-aggregate reactivity, fire due to overload, seismic forces etc. (Pardeshi et al. (2017), Kumar et al. (2021)). In this framework, non-destructive testing (NDT) techniques are commonly performed to investigate the cause of damage and to implement repair actions aimed at improving the life expectancy of reinforced concrete buildings, and restoration actions also aimed at preserving and revealing the aesthetic and historic value in the case of historic RC structures. (Sharma et al. (2016)).

NDT techniques are commonly used in the assessment of in situ characteristic concrete of existing and historical buildings, as they allow to reduce the use of semi-destructive and destructive experimental tests that inevitably require invasive sampling of materials (Santini et al. (2020)). However, NDT techniques can also integrate destructive testing techniques as in the case of the estimation of in situ concrete strength, in every case the critical step remains to correlate the NDT test results and actual concrete properties. Indeed, standards and guidelines suggest correlating these results to the ones collected through destructive tests on cores and, as a consequence, these correlations can be used to derive additional strength values from NDT results (Masi et al. (2016)).

Therefore, this contribution provides a systematic literature review based on scientific articles dealing with NDT techniques applied to historic reinforced concrete buildings. Outcomes may assist in implementing structural health monitoring and condition monitoring campaigns tailored to optimize maintenance and repair works and to extend the life expectancy of structures limiting the occurrences of failures or disruptions.

2. Methodology

The first step of the literature review included an exploratory survey to pinpoint the most common non-destructive testing (NDT) techniques employed for the condition monitoring of reinforced concrete buildings. This was done to extrapolate appropriate keywords for conducting the systematic literature review that was performed using a three-step process following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (Page et al. (2021)). The PRISMA has allowed to organize the collection and identification of relevant scientific records to be included in the analysis and review processes. The methodology conducted for the research topic is summarized in Figure 1.

The PRISMA is a three-step process: 1) Identification, 2) Screening and 3) Inclusion. The identification was conducted in *Scopus* (searching within "Article title, Abstract and Keyword") and *Web of Science* (searching within "Topic", standing for Title, Abstract, Author keywords and Keyword plus) through the combinations of a set of keywords. This search included all documents in the databases until the end of April 2023. The combination of keywords was organized in 5 strings (Table 1) where keywords have been connected via the Boolean operators "AND" and "OR". The search initially yielded to a total of 1207 records; successively, the group was reduced by excluding those documents that: (i) NOT journal articles or conference articles or book contributions, (ii) NOT available online, (iii) NOT written in English. After that, 233 duplicates were removed, bringing the total to 585 documents.

Table 1. Search strings of keyword combinations used in the PRISMA Identification step.

Research	Keyword combinations
1	Acoustic emission AND reinforced concrete AND building
2	(Ultrasonic OR impact echo) AND reinforced concrete AND building
3	Thermography AND reinforced concrete AND building
4	Rebound hammer AND reinforced concrete AND building
5	(Electromagnetic OR eddy current OR ground penetrating radar) AND reinforced concrete AND building

436 out of 585 articles were excluded after the reading of the abstract as they dealt with the following topics:

- Type of concretes containing fibers as reinforcement.
- Concrete infrastructures other than buildings.
- Very modern concrete structures (<20 years).
- Use of NDT on restoration works/repaired or treated surfaces.
- Fire/earthquakes damaged structures performance evaluation.
- Effect of thermal insulation.
- Estimation of rebar diameter, location, and cover thickness.
- Study of the electromagnetic properties of building walls.

The remaining articles were further screened by removing those presenting the use of NDT not directly performed on the structures. Consequently, 115 articles were discarded, while 32 articles were finally included and analyzed in the review.

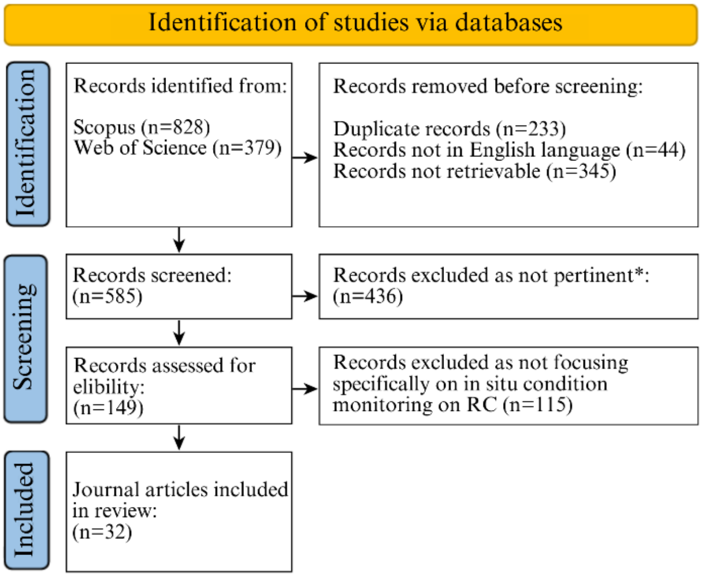

Fig. 1. Prisma flow diagram for systematic reviews showing the number of documents selected after each step.

3. Results and Discussion

3.1. NDT techniques for reinforced concrete in situ monitoring

In Figure 2 IDs are assigned to the revised articles and then reported and classified according to the NDT techniques employed in the investigations. The IDs highlighted in bold indicate works combining *in situ* and laboratory tests on real samples. Laboratory tests mainly consisted of mechanical tests (i.e., compression strength assessment through compression tests) and chemical tests (i.e., carbonation depth assessment through phenophtalein indicator). Most of the revised articles presented a combined approach between acoustic and mechanical methods, especially consisting in the *SonReb* method; a combination of Sonic and Rebound Hammer for determining concrete strength (Ji et al. (2023), Boussahoua et al. (2023), Kumar et al. (2021), Santini et al. (2020), Masi et al. (2016), Pucinotti (2015), Guida et al. (2012), Shariati et al. (2011), Pucinotti et al. (2005)).

a)

ID	Reference
1	Verstrynge et al. (2022)
2	Golewski et al. (2023)
3	Lenticchia et al. (2021)
4	Zaki et al. (2015)
5	Carpinteri et al. (2011)
6	Dixit et al. (2022)
7	Ji et al. (2023)
8	Boussahoua et al. (2023)
9	Diaferio (2022)
10	Kumar et al. (2021)
11	Santini et al. (2020)
12	Masi et al. (2016)
13	Pucinotti (2015)
14	Bjegović et al. (2013)
15	Kuznetsov et al. (2019)
16	Guida et al. (2012)
17	Shariati et al. (2011)
18	Pucinotti et al. (2005)
19	Milovanović et al. (2016)
20	Hussain et al. (2017)
21	Nguyen et al. (2022)
22	Zaki et al. (2021)
23	Kwong et al. (2020)
24	Aydin et al. (2010)
25	Venkatesh et al. (2017)
26	Tešić et al. (2021)
27	Damas Mollá et al. (2020)
28	Lachowicz et al. (2019)
29	Lachowicz et al. (2015)
30	Pérez-Gracia et al. (2008)
31	Köliö et al. (2017)
32	Carpinteri et al. (2011)

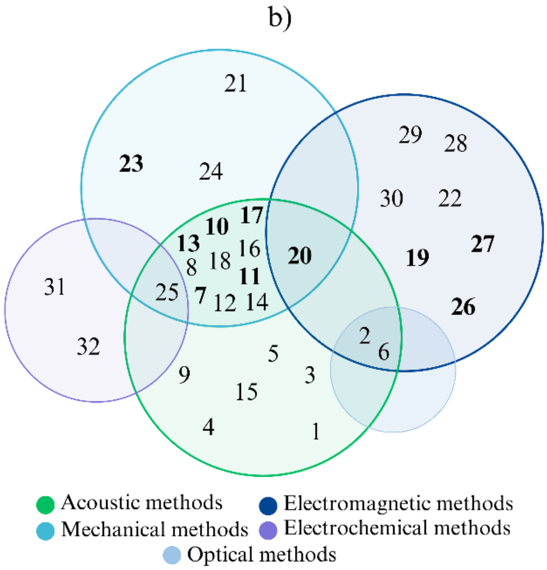

Fig. 2. (a) IDs assigned to each bibliographic reference; (b) IDs of the revised articles clustered in different categories according to the NDT method presented. IDs in bold indicate documents presenting a combined approach (in situ monitoring and in laboratory tests).

Table 2 reports an overview of NDT techniques for *in situ* detection and monitoring of reinforced concrete decay in buildings. It is worth noting that among the acoustic techniques used in the damage evolution assessment: Ultrasonic Pulse Velocity (UPV) and Acoustic Emission (AE) were the most exploited ones being cost-effective and sensitive techniques able to detect and locate the active defects (i.e., AE), and having a large penetration depth useful to estimate size, shape, and nature of the concrete damage (i.e., UPV). Ultrasonic Tomography follows the two mentioned techniques, as tomographic maps are considered to be a valid tool in the case of degradation assessment of the built heritage (mostly used to detect flaws and internal defects in concrete, as well as for rating the rebar corrosion). The Rebound Hammer, used to estimate the concrete strength and surface hardness, is frequently employed in several articles as it is simple, fast and the instrument is convenient to carry; furthermore, norms and standards have been widely formulated to guide its engineering applications. Among the electromagnetic (EM) techniques: Ground Penetrating Radar was the most used one and it has been usually employed to accurately locate and delineate rebar, flaws, cracks, and voids, even if attenuation derived from the coexisting influence with other phenomena (i.e., variations of moisture and chlorides) are unavoidable and make the results difficult to interpret. Infrared Thermography, Radiography and the others EM techniques listed in Table 2 resulted to be less frequently used (mostly to monitor flaws, cracks, voids, surface temperature and moisture content). Electrochemical techniques and Optical techniques were again less used (probably due to the high cost of the equipment especially in the latter case), but still considered reliable methods for estimating flaws and rate of corrosion by many authors.

In most documents, the results obtained are presented by the authors in a mixed way both quantitatively (i.e., through the use of graphs and tables) and qualitatively (i.e., through degradation maps and descriptions); however, the outcomes are never presented only in a qualitative way.

Table 2. Overview of NDT techniques for in situ monitoring of RC buildings according to the revised literature. The first column reports the NDT category; the second column indicates the main measurands; in the third column *PM is used for periodic measurements and CM stands for continuous monitoring; the fourth column reports the IDs of revised articles employing that technique. The last column indicates the monitored parameters of each of the applied technique.

NDT Category	Measurand	(PM)/(CM)	IDs	Monitored parameters
Acoustic				
Ultrasonic Pulse Velocity	Pulse velocity	PM/CM	2, 6, 7, 9, 13, 14, 17, 18, 20, 25	Strength, modulus of elasticity, flaws, surface hardness, rate of corrosion

Acoustic Emission	AE parameters	CM	1, 2, 3, 4, 5, 6	Rebar corrosion, concrete cracking
Ultrasonic Tomography	Wave velocity	PM	2, 11, 15	Flaws and defects internal detection, delamination/debonding
Impact Echo	Wave velocity	PM	20	Flaws and defects internal detection in concrete
Mechanical				
Rebound hammer	Rebound value	PM	7, 13, 14, 17, 18, 20, 21, 23, 24, 25	Strength, surface hardness
Electromagnetic				
Ground Penetrating Radar	Electromagnetic wave velocity	PM	20, 26, 27, 28, 29, 30	Flaws, cracks, moisture content, voids, rebar location, depth of concrete
Infrared Thermography	Radiation power	PM	19, 20, 22	Cracks, concrete quality, surface temperature
Radiography	X-ray attenuation	PM	6, 20	Surface and subsurface defects, voids, concrete quality
Eddy Current	Eddy Current	PM	6	Surface flaws, concrete cracking
Computerized Tomography	X-ray attenuation	PM	2	Flaws and defects internal detection in concrete
Electrochemical				
Half-cell potential test	Potential	PM/CM	20, 25	Carbonation depth, chloride ingress, rate of corrosion
Linear Polarization Resistance	Corrosion current	PM/CM	31, 32	Rate of corrosion
Optical				
Digital Image Correlation	Strain	CM	2	Surface flaws and cracks
Optical fiber sensors	Strain or refractive index	CM	6	Corrosion, displacement, cracks

3.2. Case-studies

The 32 articles were analyzed in terms of the type of research approach they used. It emerged that 10 out of 32 documents were review articles, although always completely or partially focused on the topic of in situ monitoring of RC buildings. The remaining majority (22 out of 32) were original research articles presenting real case studies.

In Figure 3, information about the geographical distribution, the year of construction, and the building's typology of each of the 22 real case studies is reported. In most cases, the monitored buildings were located in Europe (mainly in Italy, Spain, Poland and Finland), followed by Asia (especially in India, Vietnam and Malesia). USA and Algeria respectively presented one case for each, and four research articles did not specify the location of the monitored case studies (Figure 3a). The number of case-studies built for each time span from 1900 to 2000 is also reported in Figure 3b. Most of the monitored buildings were built between 1950 and 1975 while in 7 cases out of 22 the year of construction was not specified. In some documents, the year of construction is only approximated (i.e., the 1970s). The number of case studies is also reported for each building's typology (Figure 3c): in 6 cases, out of 22 the authors did not specify the type of monitored building, but in the remaining cases they were historic buildings in 6 cases, residential in 5 cases, civil buildings in 4 cases and industrial in just 1 case. By comparing the different case studies, the use of the same NDTs for the same type of building did not emerge, on the contrary, the same technique was frequently used to assess damage evolution in buildings with different uses. The general characteristics specified for each case study (i.e., location, year of construction and building typology) were also compared and it came out that when the location information of the case study is missing, information on the age of the building and its typology are also missing in the same articles, preventing a proper contextualization of the site.

Moreover, the most monitored zones of the reinforced concrete buildings investigated by the revised literature, were found to be the columns (Boussahoua et al. (2023), Diaferio (2022), Kumar et al. (2021), Santini et al. (2020), Masi et al. (2016), Pucinotti (2015), Kuznetsov et al. (2019), Guida et al. (2012), Shariati et al. (2011), Nguyen et al. (2022), Kwong et al. (2020), Aydin et al. (2010), Venkatesh et al. (2017)), followed by outdoor walls (Carpinteri et al. (2011), Boussahoua et al. (2023), Pucinotti (2015), Kuznetsov et al. (2019), Pucinotti et al. (2005), Lachowicz et al. (2015), Köliö et al. (2017), Carpinteri et al. (2011)), beams (Boussahoua et al. (2023), Masi et al. (2016), Pucinotti (2015), Shariati et al. (2011), Kwong et al. (2020), Venkatesh et al. (2017)), slabs (Kumar et al. (2021), Shariati et al. (2011), Kwong et al. (2020), Venkatesh et al. (2017), Damas Mollá et al. (2020), Pérez-Gracia et al. (2008)) and pillars (Lenticchia et al. (2021), Kumar et al. (2021), Lachowicz et al. (2019)). Indoor walls, staircase, and balconies were monitored in very few cases (Carpinteri et al. (2011), Kwong et al. (2020), Köliö et al. (2017)).

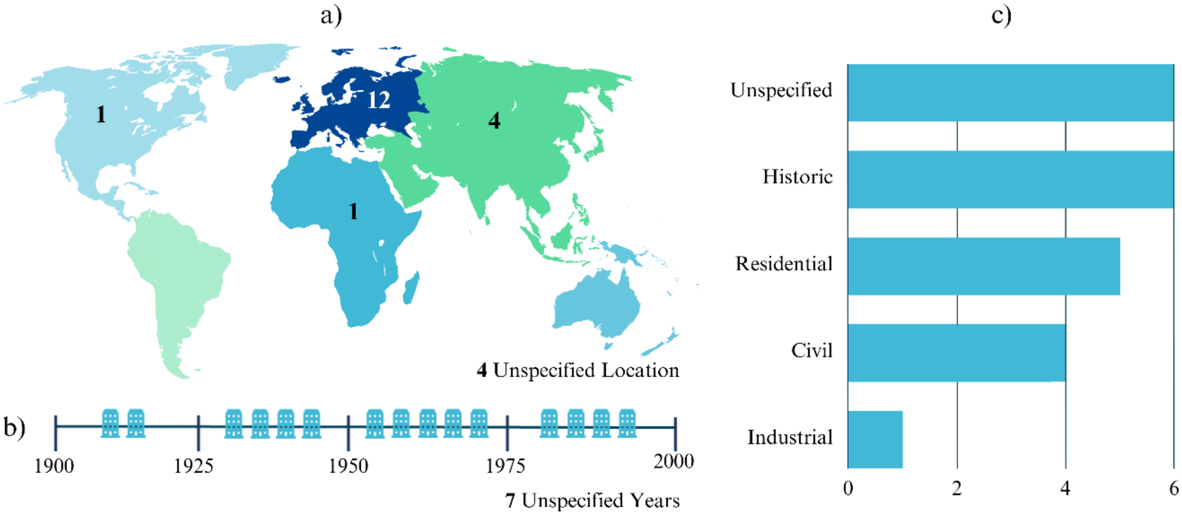

Fig. 3. Information about (a) geographical distribution; (b) year of construction; (c) building typology of the investigated case studies.

Moreover, the articles included in the present review were examined in order to comprehend the reasons behind this type of research topic. In general, the following driving motivations were obtained: assessment of the state of conservation of RC buildings (both in terms of durability and structural integrity as well as surface defects); establishment of correlation between destructive and non-destructive test results (especially in case of mechanical methods such as compressive strengths tests); formulation of appropriate sustainable measures for structural repair and rehabilitation; proposal of improvements to the current standards (both national and international) for NDT use on RC buildings (especially about sampling and evaluation) and, finally, investigation on the mechanical properties of basic materials such as steel and concrete.

Regarding the diagnosis of reinforced concrete-built heritage, among the review and original research articles, only 7 out of 32 documents dealt with historic reinforced concrete buildings. These documents (Lenticchia et al. (2021), Pucinotti (2015), Guida et al. (2012), Hussain et al. (2017), Damas Mollá et al. (2020), Lachowicz et al. (2019), Carpinteri et al. (2011)) put the emphasis on the necessity of a comprehensive understanding of the higher complexity of heritage structures, and on the need to better investigate their behavior and vulnerabilities. In this framework, the preservation of the original materials was found to be an important factor to be considered when choosing the NDT procedure to be performed in damage assessment of RC heritage structures (Hussain et al. (2017)). From here, some authors (Damas Mollá et al. (2020)) also proposed a multi-disciplinary working approach to understand the construction from its first designs to its final execution, including the characterization of current alterations. In this sense, an integration of historical, architectural, geometrical and geological studies is proposed with a common objective. The characterization of the materials used to build historic structures is said to be important to gain insight on the materials and technologies available at the time of their construction (Pucinotti (2015), Damas Mollà et al. (2020)). However, it emerged from the revised literature that only mechanical characterization of concrete is usually performed (especially to assess its strength) while concrete chemical and microstructural characteristics are usually not addressed. Only 2 articles out of 32 (Köliö et al. (2017), Carpinteri et al. (2011)), presented climate data analysis combined to the NDT test results to estimate the impact of environmental agents on the RC state of conservation.

4. Conclusions

In conclusion, the importance of RC buildings condition monitoring by NDT techniques has been widely recognized as effective in evaluating the conservation state of such structures, without causing concrete damage due to cores drilling and also allowing in situ results. Based on the outcomes of this review we can trace the main findings and what is still missing and less addressed. The main conclusions can be drawn as follows:

- As the quality of the concrete material is usually expressed as a function of its compressive strength, the combined use of acoustic and mechanical methods (also known as "SonReb" Rebound Hammer + Ultrasonic Pulse Velocity) was found to be the approach more frequently used in the revised documents, to improve the accuracy of concrete compressive strength prediction. Among the electromagnetic methods, the Ground Penetrating Radar (GPR) is one of the most widely used and validated techniques.
- Columns and outdoor walls were found to be the most monitored zones among all the revised documents. It emerged a very high variability of the mechanical properties of concrete within a whole building due to intrinsic no homogeneity, casting, curing, and different environmental degradation and accidental events which the structure can be subjected during its lifetime (factors that should be accurately considered when choosing the points to be monitored).
- Outcomes of the revised articles are usually delivered by the authors both quantitatively (i.e., graphs and tables) and qualitatively (i.e., degradation maps and descriptions), but never only in a qualitative way.

Future works in this area should be addressed to:

- Further investigate RC historic buildings in the framework of built heritage, always specifying key information for the contextualization of the case studies (i.e., location and date of construction).
- Enhance the design and performance of the various NDT detection instruments that will bring more sophisticated and sensitive devices guaranteeing reduced margins of error.
- conduct in situ indoor monitoring campaigns to assess the existing risk affecting the inner part of RC building envelopes as none of the reviewed articles dealt with indoor monitoring.
- Further explore the impact of environmental agents on RC conservation state/structural integrity thanks to a multidisciplinary approach that includes the combination of NDT test results, climate data analysis and material characterization for historic reinforced concrete buildings.

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References

Ayinde, O. O., Zuo, X. B., & Yin, G. J., 2019. Numerical analysis of concrete degradation due to chloride-induced steel corrosion. Advances in concrete construction, 7(4), 203-210.

Aydin, F., & Saribiyik, M., 2010. Correlation between Schmidt Hammer and destructive compressions testing for concretes in existing buildings. Scientific Research and Essays, 5(13), 1644-1648.

Bjegović, D., Serdar, M., Stipanović Oslaković, I., & Gulikers, J., 2013. Local detailed inspection methods to determine concrete properties on structures. Materials and corrosion, 64(2), 135-140.

Boccacci, G., Frasca, F., Bartolucci, B., Vergelli, L., Bertolin, C., & Siani, A. M., 2023. CLIMATE-INDUCED CONSERVATION RISKS OF HISTORIC REINFORCED CONCRETE BUILDINGS: PRELIMINARY RESULTS FROM LITERATURE REVIEW. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48, 227-234.

Boussahoua, Y., Kenai, S., Sbartai, Z. M., Breysse, D., & Ali-Benyahia, K., 2023. Influence of the number of cores on concrete strength assessment by nondestructive tests in old existing structures. Asian Journal of Civil Engineering, 1-15.

Carpinteri, A., Lacidogna, G., & Niccolini, G., 2011. Damage analysis of reinforced concrete buildings by the acoustic emission technique. Structural Control and Health Monitoring, 18(6), 660-673.

Crevello, G., Matteini, I., & Noyce, P., 2019. Durability Modeling to Determine Long Term Performance of Historic Concrete Structures. In Structural Analysis of Historical Constructions: An Interdisciplinary Approach (pp. 1904-1913). Springer International Publishing.

Damas Mollá, L., Sagarna Aranburu, M., Uriarte, J. A., Aranburu, A., Zabaleta, A., García-García, F., ... & Morales, T., 2020. Understanding the pioneering techniques in reinforced concrete: the case of Punta Begoña Galleries, Getxo, Spain. Building Research & Information, 48(7), 785-801.

Diaferio, M., 2022. On the Variability of Conversion Models for Concrete Strength Assessment Based on Pulse Velocity Measurements. Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems, 5(4), 041009.

Dixit, M., & Gupta, A. K., 2022. A review of different assessment methods of corrosion of steel reinforcement in concrete. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 46(2), 735-752.

Golewski, G. L., 2023. The phenomenon of cracking in cement concretes and reinforced concrete structures: the mechanism of cracks formation, causes of their initiation, types and places of occurrence, and methods of detection—a review. Buildings, 13(3), 765.

Guida, A., Pagliuca, A., & Tranquillino Minerva, A., 2012. A “Non-Invasive” technique for qualifying the reinforced concrete structure. International Journal of Geophysics, 2012.

Hussain, A., & Akhtar, S., 2017. Review of non-destructive tests for evaluation of historic masonry and concrete structures. Arabian Journal for Science and Engineering, 42(3), 925-940.

Ji, Y., Chen, A., Chen, Y., Han, X., Li, B., Gao, Y., ... & Xie, J., 2023. A state-of-the-art review of concrete strength detection/monitoring methods: With special emphasis on PZT transducers. Construction and Building Materials, 362, 129742.

Köliö, A., Pakkala, T. A., Hohti, H., Laukkarinen, A., Lahdensivu, J., Mattila, J., & Pentti, M., 2017. The corrosion rate in reinforced concrete facades exposed to outdoor environment. Materials and Structures, 50, 1-16.

Kumar, K. H., Babu, N. V., & Lingeshwaran, N., 2021. A study on repair of concrete structure using non destructive tests. Materials Today: Proceedings, 47, 5439-5446.

Kuznetsov, M. S., Maltseva, O. V., Noskov, A. S., & Kuznetsov, A. S., 2019. Experience of using the ultrasonic low-frequency tomograph for inspection of reinforced concrete structures. In IOP Conference Series: Materials Science and Engineering (Vol. 481, No. 1, p. 012047). IOP Publishing.

Kwong, T. H., Tawie, R., & Romali, S. R., 2020. Forensic to the Reinforced Concrete (RC) Structures at Library. Journal of Advanced Research in Applied Sciences and Engineering Technology, 19(1), 6-14.

Lachowicz, J., & Rucka, M., 2019. Diagnostics of pillars in St. Mary’s Church (Gdańsk, Poland) using the GPR method. International Journal of Architectural Heritage, 13(8), 1223-1233.

Lachowicz, J., & Rucka, M., 2015. Application of GPR method in diagnostics of reinforced concrete structures. Diagnostyka, 16.

Lenticchia, E., Bertetto, A. M., & Ceravolo, R., 2021. AE propagation velocity calculation for stiffness estimation in Pier Luigi Nervi’s concrete structures. Curved and Layered Structures, 8(1), 109-118.

Masi, A., Chiauzzi, L., & Manfredi, V., 2016. Criteria for identifying concrete homogeneous areas for the estimation of in-situ strength in RC buildings. Construction and Building Materials, 121, 576-587.

Milovanović, B., & Banjad Pečur, I., 2016. Review of active IR thermography for detection and characterization of defects in reinforced concrete. Journal of Imaging, 2(2), 11.

Nguyen, H. A. T., & Le, N. D. T., 2022. VERIFICATION OF DESIGN BEARING CAPACITY OF EXISTING REINFORCED CONCRETE COLUMNS. GEOMATE Journal, 23(98), 117-124.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. International journal of surgery, 88, 105906.

Pérez-Gracia, V., García, F. G., & Abad, I. R., 2008. GPR evaluation of the damage found in the reinforced concrete base of a block of flats: A case study. NDT & e International, 41(5), 341-353.

Pucinotti, R., 2015. Reinforced concrete structure: Non destructive in situ strength assessment of concrete. Construction and Building Materials, 75, 331-341.

Pucinotti, R., & De Lorenzo, R. A., 2005. In Situ Non-destructive Testing: The Steel And Concrete Resistance Assessment Of\“ancient” R/c Structures. WIT Transactions on The Built Environment, 83.

Santini, S., Forte, A., & Sguerri, L., 2020. The structural diagnosis of existing rc buildings: The role of nondestructive tests in the case of low concrete strength. Infrastructures, 5(11), 100.

Shariati, M., Ramli-Sulong, N. H., Arabnejad, M. M., Shafigh, P., & Sinaei, H., 2011. Assessing the strength of reinforced concrete structures through Ultrasonic Pulse Velocity and Schmidt Rebound Hammer tests. scientific research and essays, 6(1), 213-220.

Sharma, S., Pahuja, A., Rao, B.S., Adarsh Kumar, N.S., Sharma, A., 2016. NDT and diagnostic study of corrosion damaged RC structures to enhance their service life-case studies. Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair, pp. 87-94.

Tešić, K., Baričević, A., & Serdar, M., 2021. Non-destructive corrosion inspection of reinforced concrete using ground-penetrating radar: A review. Materials, 14(4), 975.

Venkatesh, P., & Alapati, M., 2017. Condition assessment of existing concrete building using non-destructive testing methods for effective repair and restoration-a case study. Civil Engineering Journal, 3(10), 841-855.

Verstrynge, E., Van Steen, C., Vandecruys, E., & Wevers, M., 2022. Steel corrosion damage monitoring in reinforced concrete structures with the acoustic emission technique: A review. Construction and Building Materials, 349, 128732.

Zaki, A., Chai, H. K., Aggelis, D. G., & Alver, N., 2015. Non-destructive evaluation for corrosion monitoring in concrete: A review and capability of acoustic emission technique. Sensors, 15(8), 19069-19101.

Zaki, A., Murdiansyah, L., & Jusman, Y., 2021. Cracks Evaluation of Reinforced Concrete Structure: A Review. In Journal of Physics: Conference Series (Vol. 1783, No. 1, p. 012091). IOP Publishing.