

Corrosion Monitoring Technologies for Reinforced Concrete Structures: A Review

تكنولوجيا مراقبة التآكل في الأبنية الخرسانية: دراسة

by

KHADIJA SHEHADEH

**Dissertation submitted in partial fulfilment
of the requirements for the degree of
MSc STRUCTURAL ENGINEERING
at**

The British University in Dubai

June 2023

DECLARATION

I warrant that the content of this research is the direct result of my own work and that any use made in it of published or unpublished copyright material falls within the limits permitted by international copyright conventions.

I understand that a copy of my research will be deposited in the University Library for permanent retention.

I hereby agree that the contents of this dissertation for which I am author and copyright holder may be copied and distributed by The British University in Dubai for the purposes of research, private study or education and that The British University in Dubai may recover from purchasers the costs incurred in such copying and distribution, where appropriate.

I understand that The British University in Dubai may make a digital copy available in the institutional repository.

I understand that I may apply to the University to retain the right to withhold or to restrict access to my thesis for a period which shall not normally exceed four calendar years from the congregation at which the degree is conferred, the length of the period to be specified in the application, together with the precise reasons for making that application.



Signature of the student

COPYRIGHT AND INFORMATION TO USERS

The author whose copyright is declared on the title page of the work has granted to the British University in Dubai the right to lend his/her research work to users of its library and as an open source and to make partial or single copies for educational and research use.

The author has also granted permission to the University to keep or make a digital copy for similar use and for the purpose of preservation of the work digitally.

Multiple copying of this work for scholarly purposes may be granted by either the author, the Registrar or the Dean only.

Copying for financial gain shall only be allowed with the author's express permission.

Any use of this work in whole or in part shall respect the moral rights of the author to be acknowledged and to reflect in good faith and without detriment the meaning of the content, and the original authorship.

ABSTRACT

Reinforced concrete (RC) structures are susceptible to many problems which would lead ultimately to the degradation of RC structures or a total loss in the worst-case scenario. Corrosion represents one of the main degradation sources. Due to the vital impact size of corrosion of RC structures in the form of high maintenance demand and an increase in the total life cycle cost, corrosion monitoring, early detection, and timely remediation is considered a necessity and a crucial proactive measure to control corrosion and limit its impact. In this work, the main classifications of corrosion monitoring systems were explored, highlighting their features, advantages, disadvantages, and future recommended works. To achieve that a state-of-the-art literature review was employed. Six main categories were identified from the literature: visual inspection, electrochemical methods, elastic wave methods, electromagnetic methods, fiber optic sensing methods, and mechanical methods. The subcategories of each of these were reviewed highlighting its concepts, pros, cons, and outlook and future works. Irrespective of the adopted processes for corrosion monitoring, it was concluded that none of these methods represent an optimum solution by itself, where employing a combination of multiple systems is one way of optimizing its results. New technology, algorithms, data processing, and AI are new approaches to improving corrosion monitoring processes. However, it needs further development and research.

ABSTRACT (ARABIC)

الأبنية الخرسانية عرضة للعديد من المشاكل التي من شأنها أن تؤدي في نهاية المطاف إلى تدهور هذه المباني أو خسارتها بالكلية في أسوأ الحالات. يمثل التآكل أحد المشاكل الرئيسية، نظرًا لحجم الضرر الذي يتسبب به التآكل على المباني الخرسانية في صورة طلب صيانة مرتفع وزيادة في التكلفة الإجمالية المتوقعة لإنشاء وصيانة هذه المنشآت خلال فترة استخدامها. لذلك، فإن مراقبة التآكل والكشف المبكر والمعالجة في الوقت المناسب تعتبر ضرورية وتدبيرًا استباقيًا حاسمًا للتحكم في التآكل والحد من تأثيره. في هذا العمل، تم استكشاف التصنيفات الرئيسية لأنظمة مراقبة التآكل، مع إبراز مزاياها ومزاياها وعيوبها والأعمال الموصى بها في المستقبل. لتحقيق ذلك تم مراجعة الأعمال البحثية الحديثة، حيث تم تحديد ست فئات رئيسية من أنظمة مراقبة التآكل: الفحص البصري، والطرق الكهروكيميائية، وطرق الموجات المرنة، والطرق الكهرومغناطيسية، وطرق استشعار الألياف الضوئية، والطرق الميكانيكية. تمت مراجعة الفئات الفرعية لكل من هذه الفئات مع إبراز مفاهيمها وإيجابياتها وسلبياتها وتوقعاتها وأعمالها المستقبلية. بغض النظر عن العمليات المعتمدة لرصد التآكل، فقد تم التوصل إلى أن أيًا من هذه الطرق لا تمثل الحل الأمثل في حد ذاتها، حيث يعد استخدام مجموعة من الأنظمة المتعددة مع إحدى الطرق لتحسين نتائجها. وتعد التكنولوجيا الجديدة والخوارزميات ومعالجة البيانات والذكاء الاصطناعي أساليب جديدة لتحسين عمليات مراقبة التآكل، ومع ذلك، فإنها تحتاج إلى مزيد من التطوير والبحث.

ACKNOWLEDGEMENTS

Words cannot express my gratitude to my professor and chair of my committee for his invaluable patience and feedback. I also could not have undertaken this journey without the generous support from BUID library staff who offered an extensive support to secure all the required resources for my dissertation.

Lastly, I would be remiss in not mentioning my family, especially my spouse, and children. Their belief in me has kept my spirits and motivation high during this process.

TABLE OF CONTENTS

CHAPTER ONE: Introduction.....	1
CHAPTER TWO: Literature Review.....	5
2.1 Physical and Thermal Mechanisms:.....	5
2.1.1 Vibrations and Seismic Events:.....	5
2.1.2 Freezing-thawing cycle:	6
2.2 Chemical Mechanisms:	6
2.2.1 Corrosion:.....	6
2.2.2 Sulphatic Degradation:	7
2.3 Structural Mechanisms:.....	7
2.3.1 Inadequate Design:	7
2.3.2 Improper Construction:	7
2.4 Mechanical Mechanisms:	8
2.4.1 Fatigue:.....	8
2.4.2 Abrasion:	8
2.4.3 Structural Overloading:	8
2.5 Corrosion.....	11
2.5.1 Corrosion Definition.....	11
2.5.2 Corrosion Classification	12
2.5.3 Stages of Corrosion	18
2.5.4 Factors Impacting Corrosion	20
2.5.5 Corrosion Impact on Reinforced Concrete Structures.....	26
2.6 The Power of Early Detection and Proactiveness	29
2.6.1 The Role of Corrosion Monitoring Systems	29
2.6.2 Early Detection: An Important Aspect of Infrastructure Management	30
2.7 Corrosion Monitoring Solutions:.....	30
2.7.1 Visual Inspection:.....	31
2.7.2 Electrochemical Methods:.....	33
2.7.3 Elastic Waves Methods:	41
2.7.4 Electromagnetic Methods:.....	47
2.7.5 Optical Sensing Methods:.....	55
2.7.6 Mechanical Methods:	63
CHAPTER THREE: Methodology	68
CHAPTER FOUR: Findings and Discussions	71

4.1	Visual Inspection:.....	73
4.2	Electrochemical corrosion monitoring methods:.....	74
4.3	Elastic Wave Corrosion Monitoring Methods:.....	81
4.4	Electromagnetic Corrosion Monitoring Methods:.....	85
4.5	Fiber Optic Sensing Corrosion Monitoring Methods:	92
4.6	Mechanical Corrosion Monitoring Methods:	94
CHAPTER FIVE: Outlook and Future Works		99
5.1	Visual Inspection:.....	99
5.2	Electrochemical Corrosion Monitoring Methods:.....	99
5.2.1	Half-cell Potential Measurement (Open Circuit Potential Measurements):	99
5.2.2	Electrical resistivity:.....	100
5.2.3	Linear Polarization Resistance:	100
5.2.4	Electrochemical Impedance Spectroscopy:.....	100
5.2.5	The Galvanostatic Pulse Method (GPM):	101
5.2.6	Electrochemical Noise Measurement (ENM):	101
5.3	Elastic Wave Corrosion Monitoring Methods:.....	101
5.3.1	Ultrasonic Testing (UT):	101
5.3.2	Acoustic Emission (AE):.....	102
5.3.3	Ultrasonic Pulse Velocity Test (UPV):	102
5.3.4	Impact Echo (IE):	102
5.4	Electromagnetic Corrosion Monitoring Methods:.....	103
5.4.1	Infrared Thermography (IRT):	103
5.4.2	Microwave Thermography (MWT):.....	103
5.4.3	Ground Penetrating Radar (GPR):.....	104
5.4.4	Eddy Current Testing (ECT):	104
5.4.5	Magnetic Flux Leakage (MFL):	104
5.5	Fiber Optic Sensing Corrosion Monitoring Methods:.....	105
5.6	Mechanical Corrosion Monitoring Methods:	106
CHAPTER SIX: Conclusion.....		107
REFERENCES.....		110

LIST OF TABLES

Table 1: corrosion evaluation using HCP (Anand et al. 2021; Chaudhari & Swamy 2022)	34
Table 2: LPR vs Corrosion	37
Table 3: ACI Frequency Recommendation	46
Table 4: rebound number and its interpretation.	64
Table 5: electrochemical methods pros and cons	76
Table 6: elastic wave pros and cons	82
Table 7: electromagnetic methods pros and cons	88
Table 8: fiber optic sensing methods pros and cons	93
Table 9: mechanical methods pros and cons	96

LIST OF FIGURES

Figure 1: causes of deterioration of reinforced structures (Casprini 2021).....	5
Figure 2 : RC structure relationship with deterioration and corrosion over time (Rodrigues et al. 2021).....	10
Figure 3: Concrete crack types according to their sources (Golewski 2023).....	10
Figure 4: Simplified model - corrosion electromechanical process(Quraishi et al. 2017)..	11
Figure 5: Corrosion electrochemical process (Rodrigues et al. 2021)	12
Figure 6: chloride induced corrosion (Liu et al. 2023)	15
Figure 7: carbonation induced corrosion (Liu et al. 2023).....	16
Figure 8: microcell and macrocell corrosion (NISHIDA et al. 2005)	17
Figure 9: corrosion stages (Blikharsky & Kopiika 2022)	19
Figure 10 rust expansion in uniform corrosion (Bhagwat et al. 2022)	21
Figure 11 concrete porosity and durability (Cao 2023).....	23
Figure 12: corrosion impact on RC structure (Sadeghi, Musa & Nassrullah 2019)	28
Figure 13: non-destructive corrosion monitoring.....	31
Figure 14: visual inspection site work (Zaki, Murdiansyah & Jusman 2021)	32
Figure 15: HCP Schematic(Luo et al. 2018)	34
Figure 16: HCP in action (Anand et al. 2021).....	35
Figure 17: Schematic of Four-point Wenner probe (Cheytani & Chan 2021)	36
Figure 18: LPR Measurement (Nikoo, Sadowski & Nikoo 2017).....	37
Figure 19: Rendels circuit (Daniyal & Akhtar 2020).....	38
Figure 20: Impedance components in steel concrete interface (Daniyal & Akhtar 2020) .	39
Figure 21: EIS plots (Rajendran et al. 2023).....	40
Figure 22: galvanostatic pulse method schematic(Zaki et al. 2015)	40
Figure 23: ENM connection schematic (Mills, Lambert & Yang 2021)	41
Figure 24: UT arrangement(Amiri, Erdogmus & Richter-Egger 2021).....	42
Figure 25: AE schematic(Majhi et al. 2022)	44
Figure 26: UPV test setup (Bolborea et al. 2021)	45
Figure 27: IE schematic(Zhang, Yan & Cui 2016).....	47
Figure 28: active IRT experiment setup(Zheng et al. 2022).....	49
Figure 29: MW lab test setup (Wu et al. 2021)	51
Figure 30: GPR schematic (Sossa et al. 2019)	52
Figure 31: ECT lab test setup(de Alcantara et al. 2015)	53
Figure 32: MFL test schematic (Farhangdoust & Mehrabi 2019).....	54
Figure 33: fiber sensors categories.....	56
Figure 34: FGB principle and example (Alwis, Bremer & Roth 2021).....	57
Figure 35: operating principle of quasi-distributed FBG sensor (Chen et al. 2023).....	58
Figure 36: an example of a signal's several frequency components caused by Rayleigh, Brillouin, and Raman scattering(Alwis, Bremer & Roth 2021).....	59
Figure 37: OTDR operating principle (Ye, Su & Han 2014)	60
Figure 38: OFDR schematic (Tang et al. 2021)	61
Figure 39: a. schematic of BOTDR b. schematic of BOTDA (Tang et al. 2021)	62
Figure 40: rebound hammer test schematic (Dhungana, Mishra & Aithal 2022)	65
Figure 41: pull out test setup(Nepomuceno & Bernardo 2019).....	66

Figure 42: penetration tests instruments and test setup(Al Qurishee et al. 2019).....	67
Figure 43: research methodology	70

CHAPTER ONE: INTRODUCTION

Reinforced Concrete (RC) structures have been widely used for more than a century due to their adaptability, resilience, durability, and affordability according to Chaudhari and Swamy (2022). Nonetheless, Berkowski and Kosior-Kazberuk (2017) elaborated that the performance of these structures might not be maintained over time, as they would be susceptible to premature deterioration due to a variety of causes and sources that are related to factors that may occur as early as the pre-construction phase, during construction, or after construction. The consequence of such premature deterioration varies from decreasing the structure's aesthetics (Goyal et al. 2018), to limiting the RC structure load-bearing capacity, threatening structural safety and integrity (Ge & Kim 2021).

Sources of deterioration of RC structures were listed by Casprini (2021). The main categories were physical and thermal, chemical, structural, and mechanical. Nevertheless, due to its sturdy impact on RC structures, corrosion had drawn the attention of many scholars and practitioners over the last few decades as shown in Okenyi and Alawode (2021) work. Corrosion represents an example of the chemical sources of deterioration as well as a result for many other sources as stated by Arya and Dhanya (2021), Ben Seghier, Keshtegar and Mahmoud (2021), Eldeen and Nassar (2021) and many others. As suggested by Mattsson (1999, p.11) who elaborated on this topic saying: “[T]he word corrosion comes from the Latin word ‘corrodere’, which means ‘gnaw away’. The rusting of iron and steel occur in other metals and also in non-metallic materials, such as plastics, concrete and ceramics. According to the definition, the term ‘corrosion’ stands for a process”. In recent literature corrosion is described an electro-chemical process which represents a chemical reaction and a flow of electrical current as articulated by Anand et al. (2021) and others.

In the literature of corrosion, many classifications can be found of corrosion and its sources. Nevertheless, as elaborated by Goyal et al. (2018), corrosion induced by chloride and carbonation are well studied sources due to its importance and impact. Additionally, irrespective of the source of corrosion, corrosion has two stages as discussed by Chaudhari and Swamy (2022) and others. The speed of corrosion progress within an RC structure is not an isolated process. However, as claimed by Lollini and Redaelli (2021), Trach et al.

(2023), and others, the pace of corrosion and the severity of it depend on a number of variables, including but not limited to: the environment in which the RC structure is located, the physical characteristics of the RC structure, and the calibre of the structural design.

Generally, in terms of durability, corrosion expedites the rate of a structure's degradation. It shortens the structure's useful life and frequently necessitates premature repair or replacement. As noted by Landa-Ruiz et al. (2021), this early failure violates the core principle of sustainability because it uses up more materials, labour, and energy. The generation of rubbish also rises when deteriorating structural components are taken apart and replaced. Additionally, Garca-Contreras et al. (2021) claimed that the environmental impact is influenced by the carbon footprint associated with the production of concrete and steel, as well as the environmental costs associated with the destruction and disposal of corroded structures.

Manhães et al. (2021), Majhi et al. (2022), and others stated that the rising economic and environmental costs of RC structure maintenance and rehabilitation necessitate appropriate corrosion monitoring methods. Regular and reliable RC structures inspection can reduce the economic and environmental costs of structure rehabilitation. Van Steen and Verstrynge (2021) and Tesic et al. (2022) also noted that effective corrosion monitoring and early diagnosis can help preventative maintenance plans improve structure life. Monitoring and data-driven management solutions to ensure safe use of key concrete infrastructure are crucial (Verstrynge et al. 2022).

Corrosion monitoring systems have been classified in various ways in literature. The destruction impact of the methods is of the main classifications in literature. (Álvarez, Hernández Martín and Carraz Hernández (2023) and others stated that corrosion monitoring system can be classified into destructive and Non-destructive methods where the latter one has a vital focus in the literature due to its nature. Additionally, Non-destructive techniques are also classified in literature in many means. Whether based on the nature of the monitoring process being physical or electrochemical as discussed by Verstrynge et al. (2022), or based on the classification of the process technology itself being, visual, electrochemical,

electromagnetic, etc. as elaborated by Hassani and Dackermann (2023) and others. It is noteworthy that the classification based on the process technology provides a more structured approach while reviewing the various monitoring systems.

From technology perspective, corrosion monitoring systems are classified in literature to visual inspection, electrochemical, elastic wave, electromagnetic, fiber optic sensing, mechanical and more less common system which are either in these initial stages of developments or did not earn the practitioner's attention to have enough review. Under each of these families, there are multiple methods and systems. The combinations of these methods were also discussed, and the results were analyzed. However, as suggested by Zheng et al. (2022), the performance of these combination varies.

The importance of corrosion monitoring systems can be easily seen in the literature due to the amount of research, experiments and studies which focus on the different corrosion monitoring systems. This would necessitate the need to have a collective review of the current literature to provide research with a general understanding of where the corrosion monitoring industry is today and where it is heading to close the shortcomings of today's systems. Addressing this need, this work aims to conduct a review to investigate and analyse these methods to identify their effectiveness and feasibility and recommend future works to overcome the existing solutions' shortcomings. Working toward this aim, the following objectives are sought:

- To analyse the various corrosion monitoring techniques for RC structure thoroughly.
- To present an overview of these methods that are being explored.
- To highlight the benefits and drawbacks of the different corrosion monitoring techniques from effectiveness, feasibility, cost, and outcomes perspectives, etc.
- To summarize gaps stated in the current literature and highlight the future needs for research and development.

Following this introduction, a thorough literature review was conducted addressing the concept of corrosion, its sources, categories, stages and impact on RC structures. Then, the importance of corrosion monitoring systems was established based on the current literature

to serve as an introduction for a review for the most common corrosion monitoring system available in the literature. Next is a methodology system elaborating the mechanism of conducting a state-of-the-art review. This is followed by a findings and discussion section which addresses the improvements that practitioners are currently using in their work and studies and covers the pros and cons of each of the covered techniques. Finally, outlook and future work section is dedicated to summarizing the implications and future works recommendations.

It is the researcher believe that corrosion monitoring field is an abundant field that would need more focus and further research to improve the quality of its outcomes, reduce its operational cost, and increase the feasibility and efficiency of these systems to operate at field level and provide more real time structural health status of RC structures.

CHAPTER TWO: LITERATURE REVIEW

Reinforced Concrete (RC) structures have been widely used for more than a century due to its adaptability, resilience, durability, and affordability Chaudhari and Swamy (2022). Nevertheless, Berkowski and Kosior-Kazberuk (2017) elaborated that the performance of these structures would never be maintained overtime as it would be subject to premature deterioration resultant from various reasons and sources which are related to factors that might take place as early as pre-construction phase, during construction or in post construction phase. These reasons can be summarized as shown in figure 1 and listed in the following categories:

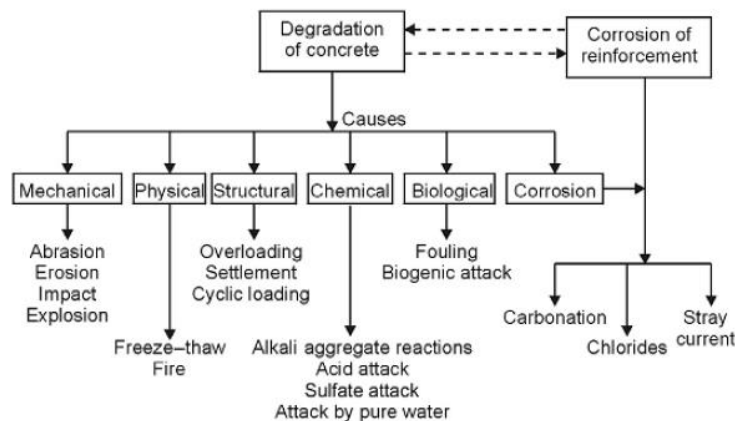


Figure 1: causes of deterioration of reinforced structures (Casprini 2021)

2.1 Physical and Thermal Mechanisms:

2.1.1 Vibrations and Seismic Events:

Machine vibrations, earthquakes, or construction operations can cause structural discomfort, resulting in cracks, dislocations, or failure (Blikharsky & Kopiika 2022).

2.1.2 Freezing-thawing cycle:

structures subjected to freezing temperatures and the resulting icing-deicing cycle are vulnerable to damage. Water expansion during freezing and thawing can result in cracking, spalling, and surface degradation (Wan-Wendner 2018; Hariri-Ardebili, Sanchez & Rezakhani 2020).

- 1.1. Fire: fires can cause severe structural damage, jeopardizing their integrity and causing structural discomfort. High temperatures can cause material weakness, thermal expansion, and collapse (Wan-Wendner 2018; Alhamad & Eid 2020).
- 1.2. Concrete creep and shrinkage: creep and shrinkage are critical variables in guaranteeing the safety and functionality of concrete buildings. Creep refers to deformation under prolonged load, whereas shrinkage is the shortening induced by water loss. In high-rise buildings, creep can cause large relative deformations between columns and the concrete core. Shrinkage can cause cracking in mass structures and constraint loads in statically indeterminate frames (Wan-Wendner 2018; Hariri-Ardebili, Sanchez & Rezakhani 2020).

2.2 Chemical Mechanisms:

2.2.1 Corrosion:

Corrosion is inevitable in environments where RC structures are exposed to fluctuating temperatures, high chloride concentrations, extreme humidity, etc. (Rao & Sasmal 2022). These conditions would stimulate an electrochemical reaction that would lead to an electrical current flow and a chemical reaction. This would have an adverse effect on the steel protective layers, influencing the steel-concrete bond strength and the overall performance of the RC structure (Quraishi et al., 2017). In the same context, Zhang et al. suggested that because of environmental variability, randomization in material properties, and diversity in concrete coverings, corrosion of concrete reinforcement is now thought to be a random process (2021). However, irrespective of its randomness, as argued by Rodrigues et al. (2021) and many other scholars, corrosion represents the main cause for RC structure deterioration.

2.2.2 Sulphatic Degradation:

RC structures can degrade when exposed to sulphate-rich environments, which are often present in soil or groundwater. This type of sulphatic attack is defined by Shi and Mo (2008) external source attack. Furthermore, they stated that sulphatic attack might be due to internal sources, for example: a high sulphate ratio in cement.

- 1.1. Acid, Alkali, Chlorine and salt attacks and aggregate acid reaction (AAR) are other examples for chemical driven deterioration as argued by Hammad, Shafiq and Nuruddin (2018).

2.3 Structural Mechanisms:

2.3.1 Inadequate Design:

Defects or flaws in structural design which are, as argued by Peansupap and Ly (2015), resultant from, but not limited to: the lack of design requirements clarity, lack of collaboration between the different design teams involved, in addition to the lack of design optimization expertise. Such early failures might lead to inadequate reinforcing, insufficient load-bearing capability, or incorrect detailing which would ultimately impact the overall RC structure performance and increase its maintenance requirements and cost (Berkowski, Dmochowski & Kosior-Kazberuk 2013; Peansupap & Ly 2015).

2.3.2 Improper Construction:

As highlighted by Berkowski and Kosior-Kazberuk (2017) it is undeniable that human behaviours and practices would have a significant impact on the overall service life of any RC structure. Poor workmanship, insufficient quality control, inappropriate materials selection or improper construction procedures can all contribute to RC structure deterioration. Such irresponsible actions might cause cracking, settlement, or uneven load distribution.

2.4 Mechanical Mechanisms:

2.4.1 Fatigue:

Fatigue is the degradation of a substance caused by repetitive loading and unloading, also known as cyclic loading, which results in gradual and localized damage. Liu et al. (2023) studied this phenomenon and clarified that chronic fatigue loading also results in Cracking in concrete and pore structure deterioration, hastening the entrance of external corrosive chemicals and decreasing concrete durability. Long-lasting vulnerability to corrosive conditions reduces the endurance of concrete and causes corrosion of reinforcement parts, decreasing the structure's fatigue efficiency.

2.4.2 Abrasion:

Wu, Chen and Chen (2023) explained that abrasion is a phenomenon caused by friction, scratching, and pounding that reduces the volume and mass of the material surface; consequently, it is promising to adjust the surface characteristics for abrasion resistance increase. Abrasion failure, on the other hand, differs from other durability difficulties, such as freeze-thaw cycles, chemical ion assaults, and impact failure, because abrasion failure typically occurs only on the concrete surface and does not cause serious damage to the internal concrete matrix. The quality of the surface layer has a greater impact on anti-abrasion performance than the matrix performance of concrete.

2.4.3 Structural Overloading:

Trach et al. (2023) argued that structural overloading is another mechanical issue that leads to RC structure deterioration. When an RC structure is subjected to loads that exceed its designed capacity, microcracks in the concrete can form, enabling corrosive substances such as chlorides and carbon dioxide to enter. These elements can eventually reach the reinforcing steel and induce corrosion. As a result, sticking to a structure's design load limits can help to reduce the danger of corrosion (Krentowski 2021).

Despite the fact that RC structures' deterioration might be caused by any of the listed causes, scholars have broadly agreed that corrosion remains the dominant cause of reinforced concrete (RC) structure deterioration, frequently resulting in greater structural damage than

other causes of deterioration as stated by Arya and Dhanya (2021), Ben Seghier, Keshtegar and Mahmoud (2021), Eldeen and Nassar (2021), García-Contreras et al. (2021), Li et al. (2021), Ramani and Kuang (2021), Rodrigues et al. (2021), Zhang et al. (2021) and many other scholars . According to a study by Verstrynge et al. (2022), a significant portion of all costs associated with concrete restoration and maintenance are attributable to corrosion of steel reinforcement. In similar context, Zhang et al. (2021) documented that the cost of street and bridges corrosion maintenance represents around 3.34% of China Gross Domestic Product (GDP). Nevertheless, despite its cost, corrosion cannot be neglected or overlooked as this procedure reduces the cross-sectional area of steel, thereby jeopardizing the structural integrity of RC structures and represent a life-threatening risk (Daniyal & Akhtar 2020). Corrosion impact is not only limited to the increase of maintenance demands and cost, but also it might represent a life-threatening risk to RC buildings residents. As concluded by a recent study carried out by Dogan, Hakan Arslan and Ilki (2023) in Turkey to detect damages resultant from earthquake and RC corrosion structure, corrosion contributed to the weakness of the old buildings' seismic resilience. Similar incidents were reported in Italy as well as the USA where tens of people lost their lives in RC structures collapse. Investigation showed that corrosion was a significant contributor that led to the collapse as reported by (Verstrynge et al. 2022).

However, other causes of deterioration, such as freeze-thaw cycles and alkali-silica reaction (ASR), must not be ignored. For example, repeated freeze-thaw cycles can cause concrete to expand and contract, resulting in fractures which would create a path of the external water and humidity to penetrate the concrete increasing the potential of facing harsh corrosion and its consequences (Guo et al. 2022). In a similar manner, ASR is caused by a reaction between reactive silica in the aggregate and alkalis in the cement, resulting in expansive pressures and eventual fractures and the inevitable costs of corrosion (Luo, Asamoto & Nagai 2023). Figure 2 below, explain the effect of these conditions and its link to the corrosion over time.

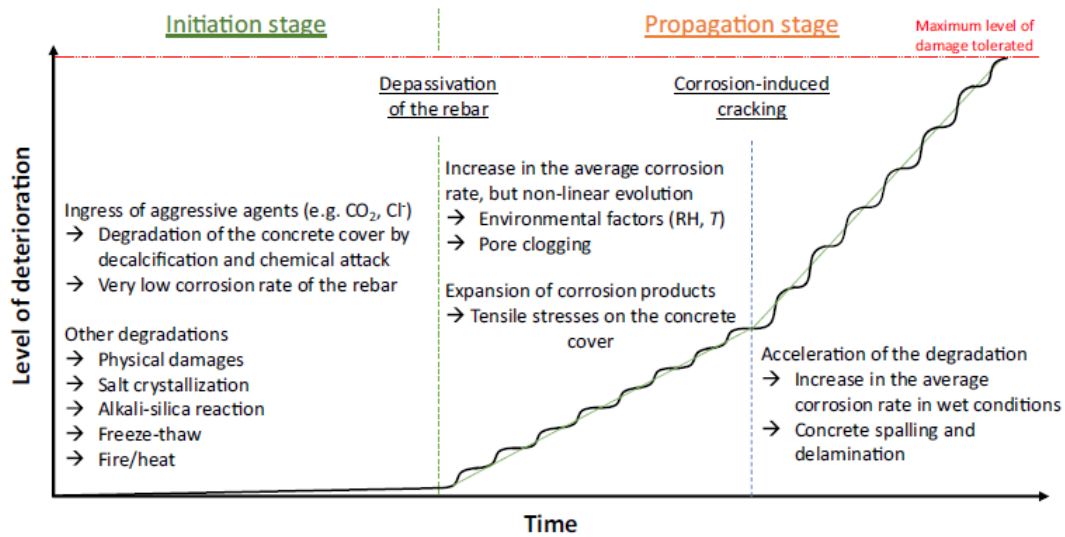


Figure 2 : RC structure relationship with deterioration and corrosion over time (Rodrigues et al. 2021)

Although these factors contribute substantially to the deterioration of RC structures, their effects are typically more localized in the form of cracks and frequently less severe than corrosion. Figure 3 below shows the common sources of cracks in RC structures. In addition, corrosion can manifest as a cumulative effect of these factors, highlighting its crucial role in the process of deterioration. Therefore, the significance of corrosion as a cause of deterioration in RC structures remains substantial (Golewski 2023).

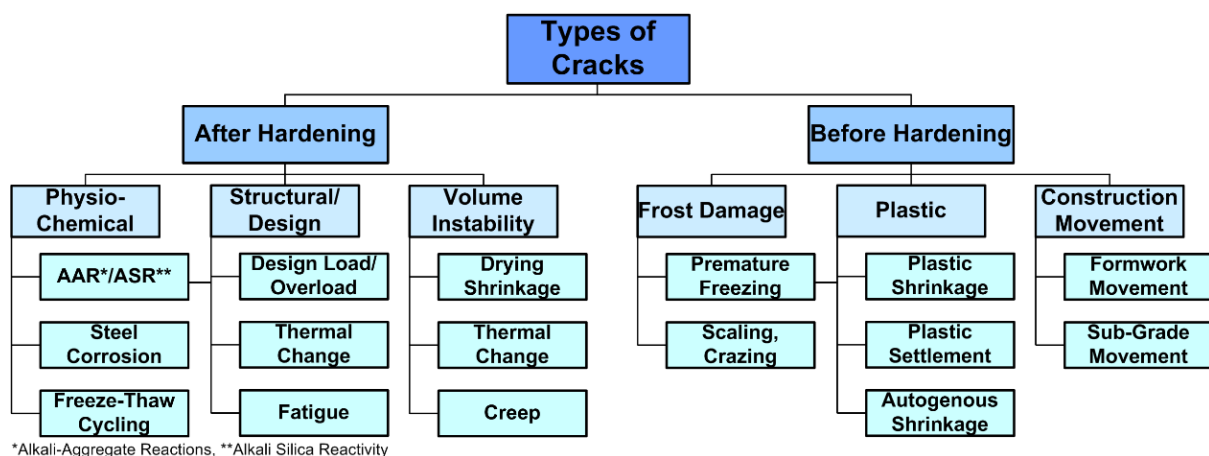


Figure 3: Concrete crack types according to their sources (Golewski 2023)

2.5 Corrosion

2.5.1 Corrosion Definition

Corrosion as a word had a Latin route as suggested by Mattsson (1999, p.11) who elaborated on this topic saying: “[T]he word corrosion comes from the Latin word ‘corrodere’, which means ‘gnaw away’. The rusting of iron and steel occur in other metals and also in non-metallic materials, such as plastics, concrete and ceramics. According to the definition, the term ‘corrosion’ stands for a process”. From a structural engineering point of view, corrosion as argued by Quraishi et al. (2017), Sadeghi, Musa and Nassrullah (2019), Anand et al. (2021) Eldeen and Nassar (2021) and Chaudhari and Swamy (2022) is a phenomenon which leads a substance to deteriorate or annihilate when exposed to diverse environmental conditions. Concrete corrosion is an electrochemical process that involves both the flow of electrical current and chemical reactions. Because of the alkalinity (pH between 12 and 13) of the concrete, the steel in reinforced concrete structures is in a passive condition and is covered by a thin coating of oxide. Figure 4 and 5 shows the electro-chemical process of corrosion.

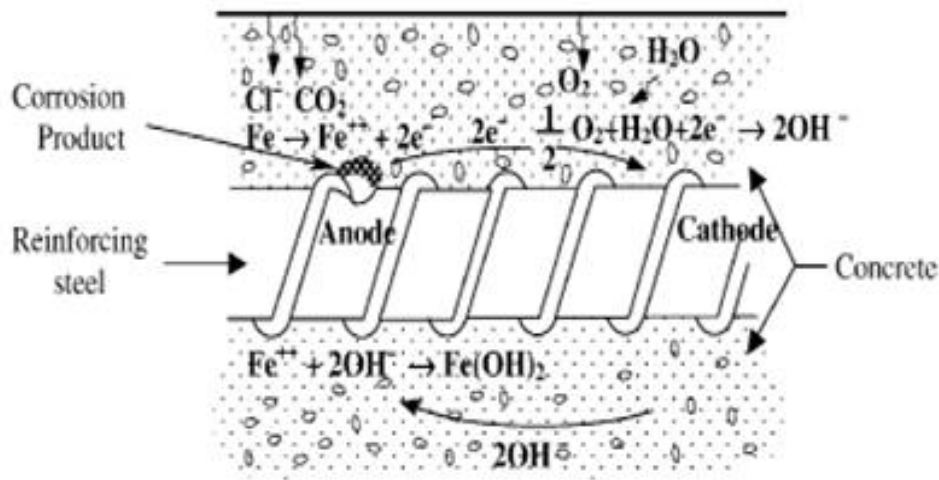


Figure 4: Simplified model - corrosion electromechanical process(Quraishi et al. 2017)

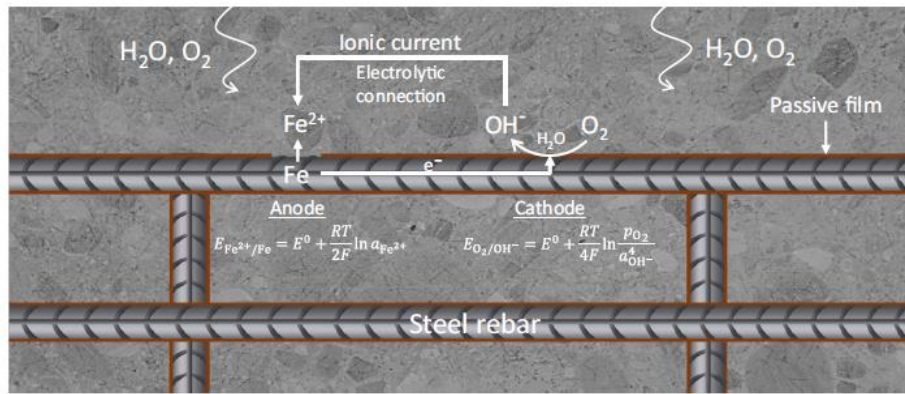


Figure 5: Corrosion electrochemical process (Rodrigues et al. 2021)

2.5.2 Corrosion Classification

Corrosion, in literature, has been classified according to multiple criteria where different criteria resulted in different views of types of corrosion. Corrosion location and mechanism are some of these criteria. Below are few of the most common corrosion types in literature:

General or Uniform Corrosion

The most common variety of corrosion, uniform, or general corrosion produces a uniform layer of corrosion products over the entire exposed surface or large areas. This form of corrosion typically occurs at a rate that is predictable and can be measured by weight loss over time. For example, iron in a humid environment rusts uniformly. Despite causing substantial material loss over time, uniform corrosion is considered less dangerous than localized corrosion because its symptoms are visible and allow for early detection and mitigation (Sadeghi, Musa & Nassrullah 2019; Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Localized Corrosion

Localized corrosion, on the other hand, affects specific regions of a material, resulting in isolated but severe damage. This category comprises corrosion in pits, crevices, and between grains (Sadeghi, Musa & Nassrullah 2019; Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Pitting corrosion is characterized by the presence of tiny holes or "pits" on the surface of a material. Although the overall material loss may be minimal, the resulting damage can considerably compromise the material's structural integrity (Sadeghi, Musa & Nassrullah 2019; Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Crevice corrosion occurs in confined, shielded spaces or cracks on the surface of a material. These crevices may contain differential aeration cells, resulting in an aggressively corrosive environment within the crevice. Crooked joints are famous example of this specific type of corrosion (Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Intergranular corrosion targets a material's grain boundaries in particular. In many alloys, impurities or different phases concentrate at grain boundaries, rendering these regions more anodic than the grains. However, among the various localized corrosion, intergranular corrosion is less common in RC structures (Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Galvanic Corrosion

When two dissimilar metals are in physical or electrical contact and exposed to an electrolyte, galvanic corrosion occurs. The nobler metal serves as the cathode, while the less noble metal serves as the anode, resulting in preferential corrosion of the anodic material. In marine environments, where saltwater serves as an effective electrolyte, this form of corrosion is especially prevalent (Eldeen & Nassar 2021; Harsimran, Santosh & Rakesh 2021).

Erosion Corrosion

Erosion Due to fluid flow, corrosion is caused by a combination of chemical attack and physical attrition. Abrasion continuously removes the protective oxidation layer from the metal surface, exposing the underlying material to further corrosion. On the surface of the

material, this type of corrosion frequently manifests as fissures, gullies, or wave patterns (Harsimran, Santosh & Rakesh 2021; Zarrabi, Moghim & Eftekhar 2021).

SCC - Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the fracture of materials caused by the presence of tensile stress and a corrosive environment simultaneously. External burdens, residual stresses from manufacturing processes, or both can induce stress. Certain environments can increase a material's susceptibility to SCC, resulting in a sudden and unanticipated material failure (Goyal et al. 2018; Martin et al. 2020; Harsimran, Santosh & Rakesh 2021) .

Corrosion by Selective Dissolution (Dealloying)

Selective dissolution, also known as dealloying, is the process of a specific alloy component seeping out selectively in a corrosive environment. The resulting structure is compromised and porous. This process is exemplified by the dezincification of brass, in which zinc dissolves, leaving behind a porous, copper-rich structure that compromises the mechanical strength and integrity of the brass (Sadeghi, Musa & Nassrullah 2019; Eldeen & Nassar 2021).

Corrosion Induced by Chloride

One of the primary causes of corrosion of reinforcing elements inside RC structures is chloride ion infiltration. Cement hydration products with high pH can generate a dense oxide film on the surface of reinforcement components inside concrete, preventing corrosion of those materials. Because chloride ions have a strong de-passivation characteristic, when the oxide film is exposed to adequate amount of chloride ions through the concrete's connected pores and cracks, the pH of the surrounding pore solution drops and the protective film is destroyed, allowing reinforcement material corrosion. Furthermore, chloride ions can act as catalysts, promoting the corrosion reaction without being consumed. As a result, chloride ions getting in the concrete can constantly degrade the structure, which is the basic feature of chloride corrosion (Goyal et al. 2018; Eldeen & Nassar 2021; Rodrigues et al. 2021;

Verstrynge et al. 2022; Liu et al. 2023). For example, pitting corrosion is a typical example of a chloride induced corrosion and its graphic representation is depicted in Figure 06.

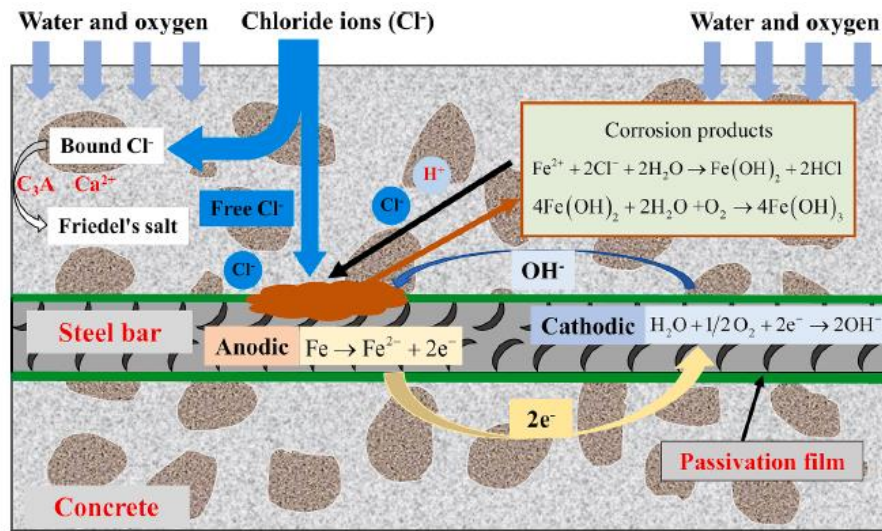


Figure 6: chloride induced corrosion (Liu et al. 2023)

The movement of chloride ions through microcracks and holes in concrete is a complex process that involves at least six different forms of action: diffusion, convection, adsorption, electromigration, penetration, and capillary. The common transmission processes include diffusion, penetration, and capillary action, with diffusion being the primary process for chloride transfer in saturated concrete (Coppola et al. 2020; Liu et al. 2023).

Corrosion Caused by Carbonation

Carbonation is one of the most common causes of deterioration in the performance of RC structures and more frequent than chloride attack and freeze-thaw cycles. Carbonate and bicarbonate ions are formed when carbonate and bicarbonate ions permeate into the concrete through linked pores and defects such as microcracks generated by autogenous shrinkage or drying shrinkage. Following that, these compounds can react with primary hydration products such as calcium hydroxide, C-S-H gels, and even unhydrated tricalcium silicate and dicalcium silicate to generate calcium carbonate and other salts, resulting in a decrease in concrete alkalinity. As a result, concrete carbonation is also known as the neutralization reaction of concrete. Carbonation, in general, has no influence on the qualities and performance of the concrete materials, and even improves internal pore structures and boosts density due to the formation of carbonation salts. When the carbonation is close to the surface

of the reinforcement material within the concrete, the pore solution with a low pH value might make the passivation film on its surface unstable, eventually dissolving it and causing reinforcement material corrosion. In contrast to chloride-induced steel corrosion, concrete carbonation results in homogenous deterioration of the reinforcing surface. Figure 07 depicts the rusting mechanism produced by carbonation. Furthermore, corrosion product expansion will create cracks in the concrete matrix, hastening the entrance of external corrosive substances and jeopardizing the overall integrity of the concrete structure (Goyal et al. 2018; Rodrigues et al. 2021; Verstrynge et al. 2022; Zhang et al. 2022; Liu et al. 2023).

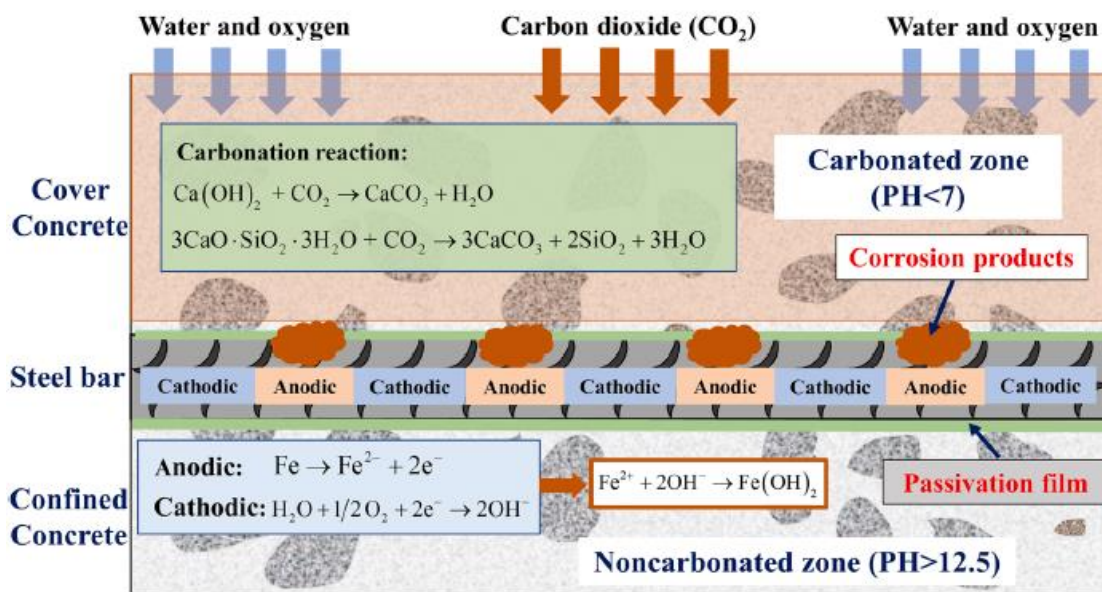


Figure 7: carbonation induced corrosion (Liu et al. 2023)

In the literature, other classifications can be found, where, based on the electrochemical process of corrosion, rebar corrosion caused by micro-corrosion cells (referred to as microcell corrosion of steel rebar) and rebar corrosion induced by macrocorrosion cells (referred to as macrocell corrosive of steel rebar) can be generally differentiated as discussed by Wang et al. (2023). Figure 8 below show the schematic of the two types.

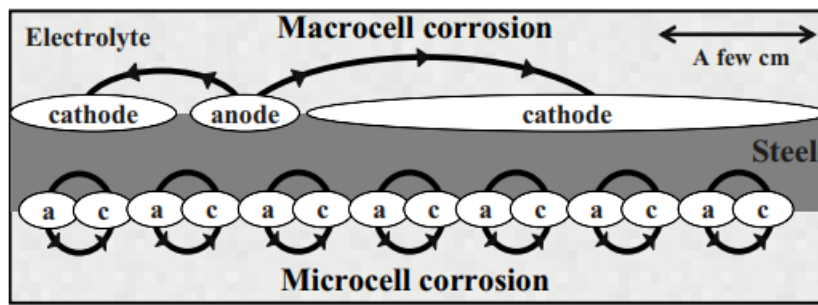


Figure 8: microcell and macrocell corrosion (NISHIDA et al. 2005)

Corrosion of Microcells

Microcell corrosion happens on steel rebar in a highly restricted location. As articulated by Rodrigues et al. (2021), and Lliso-Ferrando et al. (2022), this sort of corrosion occurs when there is a high concentration of aggressive substances, such as chlorides, near the rebar. A small region on the steel surface acts as an anode (where the metal corrodes), while a neighboring area acts as a cathode (where reduction reactions take place). These zones are often in the micrometer range, therefore the phrase "microcell corrosion".

Li et al. (2023) and Wang et al. (2023) elaborated that the anodic and cathodic processes occur relatively close together in microcell corrosion, causing corrosion to advance in a more uniform but concentrated manner. This process can cause pitting of the steel surface, which causes small pits or 'holes' to form, resulting in a significant reduction in the cross-sectional area of the steel rebar. Due to the concentrated form of the material loss, pitting corrosion can considerably damage the load-bearing capacity of steel rebar despite the reduced area of steel loss.

Corrosion of Macrocells

Macrocell corrosion, on the other hand, affects greater sections of the steel reinforcement and might even involve various bars or steel components within the same RC structure. As Lliso-Ferrando et al. (2022) described, this sort of corrosion occurs when there is an

electrical connection between rebars positioned in different concrete environments, such as when the chloride concentration differs.

In macrocell corrosion, (Li et al. 2023) detailed that one rebar (or part of a rebar) corrodes in a more aggressive environment, while another rebar (or portion of a rebar) corrodes in a less aggressive environment. The presence of a conducting medium, such as the concrete pore solution, allows ions to flow, while the metallic link through the rebars allows electrons to flow.

Macrocell corrosion causes more generalized, or uniform, corrosion along the rebar, resulting in broad steel thinning. Though the material loss is less concentrated than in microcell corrosion, the level of overall degradation can nonetheless jeopardize the RC structure's structural integrity (Rodrigues et al. 2021; Wang et al. 2023).

2.5.3 Stages of Corrosion

Corrosion is a major worry for structural engineers and building owners worldwide, particularly in reinforced concrete (RC) constructions. The steel reinforcement contained within the concrete corrodes with time, compromising the durability and safety of RC structures. It is critical to understand the two primary stages of corrosion: initiation and propagation (as shown in figure 9 below), in order to better manage the dangers connected with this harmful process.

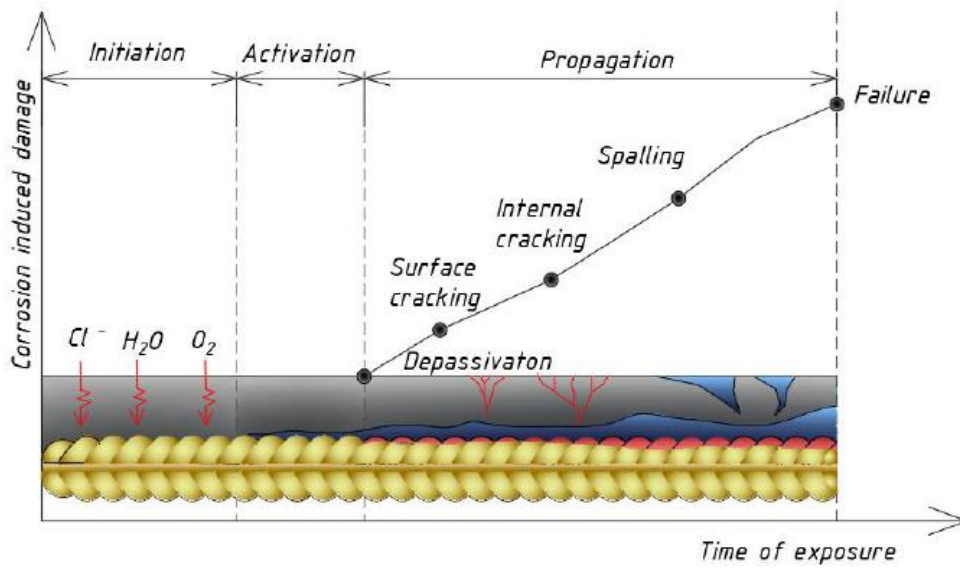


Figure 9: corrosion stages (Blikharsky & Kapiika 2022)

Phase One: Initiation

In RC structures, the initiation phase is the start of the corrosion process. The surrounding concrete's strong alkalinity (pH of roughly 12.5-13.5) protects the steel reinforcement bars (rebars) from corrosion at first. This alkaline climate causes the creation of a passive layer on the steel surface, a thin film of iron oxide that aids in corrosion prevention. This protective layer, however, can be dissolved over time by two principal mechanisms: carbonation and chloride assault as described by Chaudhari and Swamy (2022), Chaudhari and Swamy (2022), and Blikharsky and Kapiika (2022).

As clarified by Angst (2018), Eldeen and Nassar (2021), and Maheshwari and Rao (2022) carbonation occurs when ambient carbon dioxide (CO_2) combines with the calcium hydroxide in the concrete to generate calcium carbonate (CaCO_3), lowering the pH. When the carbonation front reaches the rebars, the passive layer is destroyed, exposing the steel to corrosion.

Chloride attack, on the other hand, happens when chloride ions enter the concrete and reach the steel reinforcement from sources such as de-icing solutions or seawater. These ions can directly disrupt the passive layer, resulting in localized points of attack, as explained by Wan-Wendner (2018), Eldeen and Nassar (2021), and Hu et al. (2022).

Second phase: propagation

The corrosion process enters the propagation phase when the initiation stage has undermined the protective environment. According to Goyal et al. (2018), Chaudhari and Swamy (2022) and Verstrynge et al. (2022), the steel reinforcement is actively corroded at this phase. In the corrosion reaction, iron (Fe) in the steel reinforcement is converted to iron oxide (Fe_2O_3) or hydroxide ($\text{Fe}(\text{OH})_3$). The steel serves as the anode and cathode in this electrochemical process. The iron loses electrons at the anode and turns into positively charged iron ions, which react with water and oxygen to generate iron oxide or hydroxide.

Zhang et al. (2019), Miró et al. (2021) and Bhagwat et al. (2022) explained that because the corrosion products take up more space than the initial iron, their production causes enormous internal pressure to build up within the surrounding concrete. This pressure causes cracks, spalling, and delamination in the concrete cover, exposing more steel to the environment and hastening the corrosion process. If not mitigated, this can cause substantial damage to the RC structure over time, reducing its load-bearing capacity and structural integrity.

2.5.4 Factors Impacting Corrosion

Corrosion is a result of an electrochemical reaction that would happen between the RC structure materials and the surrounding environment. However, as argued by Lollini and Redaelli (2021), Trach et al. (2023), and others, the rate of corrosion, and its severity depend on multiple factors including but not limited to: the nature of the surrounding environment, the RC structure physique and quality of the structural design itself. These factors can be elaborated as follows:

1- RC structure vulnerability to surrounding environment conditions:

RC structure durability and its performance are susceptible to different environmental conditions. Zhang et al. (2021) argued that these conditions would ultimately impact its characteristics over time and might result in a total loss for the RC structure in severe

conditions. The same conclusion was also emphasized by Ge and Kim (2021). These factors can be classified into:

1.1. Corrosion and Moisture

Moisture, whether it comes from rainfall, air humidity, or immersion in aquatic bodies, is the most important component in RC corrosion. As elaborated by Bhagwat et al. (2022) and Blikharsky and Kopiika (2022) Rust (iron oxide), which can occupy as much as six times the space of the original steel, forms when oxygen and moisture are present, which causes steel reinforcement in concrete to corrode. Tensile stresses are produced by this expansion, which cause cracking, delamination, and eventually spalling of the concrete cover as simplified in figure 10 below.

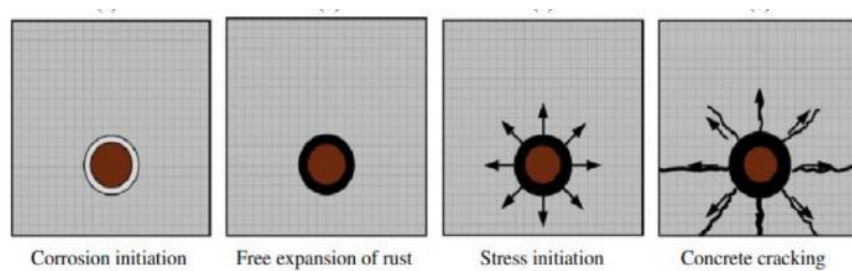


Figure 10 rust expansion in uniform corrosion (Bhagwat et al. 2022)

1.2. Corrosion Caused by Chloride

Chlorides can speed up corrosion rates in RC structures. They are frequently found in seawater, deicing salts, and some groundwaters. These ions pierce the concrete and damage the steel's imbedded passive oxide layer, causing pitting corrosion as explained by Verstrynge et al. (2022) and Goyal et al. (2018). Structures near coasts and those exposed to de-icing salts in cold regions are particularly susceptible to corrosion brought on by chloride. This process over time can seriously reduce the RC constructions' ability to carry loads (Rodrigues et al. 2021).

1.3. Corrosion Caused by Carbonation

Through a process known as carbonation, as explained by Anand et al. (2021), and Eldeen and Nassar (2021), exposure to carbon dioxide (CO₂) in the environment has an impact on RC structure corrosion as well. Concrete's calcium hydroxide and atmospheric CO₂ combine to generate calcium carbonate, which lowers the concrete's alkalinity and the reinforcement's protective oxide layer. The steel becomes more prone to corrosion as a result of this process, especially in cities with high CO₂ levels.

1.4. Variations in temperature

Variations in the outside temperature have an impact on how quickly RC structures corrode. By accelerating chemical reactions and raising the pace at which hazardous ions diffuse into the concrete by damaging the protective layer Blikharsky and Kopiika (2022), high temperatures can hasten corrosion. On the other hand, as argued by Guo et al. (2022) cold temperatures can result in freeze-thaw cycles, which can cause fissures that make it easier for corrosive substances to access the reinforcement.

1.5. Collective Effects

Verstrynge et al. (2022) argued that these environmental factors can have a combined negative effect that is greater than their individual effects. For instance, moisture and chlorides frequently work together synergistically to speed up corrosion. Similar to carbonation, chloride attacks can sometimes happen simultaneously, leading to serious corrosion problems in some environments (Rodrigues et al. 2021).

2. RC structure physique influence

Similar to any other man-made artifact, the quality, durability, performance of the produced artifact and its vulnerability to premature failure would depends on the quality of its raw materials and the performed workmanship. RC structure is no different, where its raw materials and the workmanship during the construction process are kay factors for its immunity to premature failures caused by corrosion or any other external factor (Lollini & Redaelli 2021).

2.1. Corrosion and Concrete Quality

The durability and corrosion resistance of RC structures are strongly influenced by the concrete mix utilized for their construction. The water-cement ratio, cement type and quantity, aggregate quality, and the presence of admixtures are only a few of the variables that affect concrete quality (Sadeghi, Musa & Nassrullah 2019; Kasassbeh, Tamseh & Kharabsheh 2020; Lollini & Redaelli 2021; Rodrigues et al. 2021; Chaudhari & Swamy 2022).

2.1.1. Water-cement ratio

As discussed by Cao (2023), greater concrete porosity makes it more porous and therefore more porous to corrosive chemicals, which in turn causes reinforcing steel to corrode more quickly. Conversely, lower water-cement ratios result in denser, more robust concrete that has better corrosion resistance (da Silva et al. 2020). The relationship between concrete porosity and durability is shown in figure 11 below.

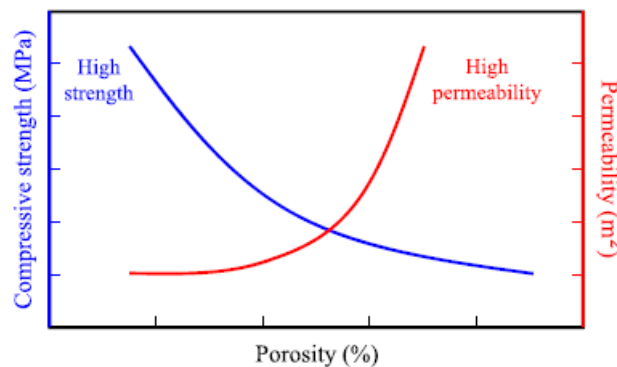


Figure 11 concrete porosity and durability (Cao 2023)

2.1.2. Cement type and quantity:

As suggested by Chalhoub, François and Carcasses (2020) the type of cement is one element that may affect corrosion start by altering the microstructure at the steel-concrete interface, as well as by affecting the pH of the pore solution and the ability of the material to bind chloride.

2.1.3. Quality of the aggregates:

As argued by Baltazar-García et al. (2022) the use of high-quality aggregates (for example: recycled concrete aggregates) makes concrete less prone to cracking and spalling and shield the reinforcing steel from corrosive elements, as it would help to avoid the negative consequences of the use of contaminated aggregates as elaborated by (Verstrynge et al. 2022).

2.1.4. Admixtures:

Eldeen and Nassar (2021) and Landa-Ruiz et al. (2021) stated that the presence of admixtures can considerably improve concrete's immunity to corrosion. Examples include fly ash, silica fume, and slag. They lessen permeability and improve concrete density, hence lowering the risk of corrosion.

2.2. Corrosion and Construction Practices:

In RC buildings, the danger of corrosion can be significantly reduced by using good construction techniques. These procedures cover the proper mixing, pouring, curing, and protection of the reinforcement for concrete (Kasassbeh, Tamseh & Kharabsheh 2020).

2.2.1. Concrete mixing and placement:

Making sure that concrete is mixed evenly and placed correctly prevents the build-up of voids and honeycombs, that can raise the danger of corrosion. Inadequate vibration while placement can also cause disparities in distribution and compaction, which can result in the segregation of the concrete (PCA 2002; Abdel Rahman 2007).

2.2.2. Curing:

The strength and longevity of the concrete are affected by proper curing; thus it is crucial. Insufficient curing may cause the concrete to become more porous, which would make it more susceptible to corrosion (Baltazar-Zamora et al. 2020).

2.2.3. Protection of the reinforcement:

As discussed by Bhagwat et al. (2022), to avoid the direct exposure of steel to hostile substances, the proper positioning of reinforcement with sufficient concrete cover is essential. i.e. the thicker the concrete cover is, the more shield the RC structure has against corrosion. Site engineers and implementation team shall not ignore the recommendation coming from the designers for the details of the reinforcement implementation.

3. RC structure design Influence

Corrosion can also be exacerbated by structural design. Designs that unintentionally encourage water collection, especially in gaps, create an excellent environment for corrosion as studied by Berkowski and Kosior-Kazberuk (2017). Major design aspects that would influence RC structure corrosion are as below:

3.1. The Effect of Structural Dimensions

As detailed by Bhagwat et al. (2022) the dimensions of an RC structure have a direct impact on its corrosion resistance. Particularly important are the dimensions and placement of reinforcement bars. When reinforcement bars are tightly spaced or oversized, higher stress concentrations might occur, resulting in concrete cracking. This fracture accelerates the admission of hazardous materials such as chloride ions, that are the primary driver of reinforcement corrosion. Effectively spaced and proportioned reinforcing, on the other hand, decreases stress concentrations and subsequent cracking, eliminating the paths for hazardous chemicals and therefore reducing corrosion potential.

3.2. The Impact of Concrete Coverage

AS studied, analysed, and concluded by the field survey and laboratory study of Asamoto et al. (2021), the volume, as well as the quality of the concrete cover, are critical design criteria that influence reinforcement corrosion in RC structures. The concrete cover serves as a physical barrier to corrosive substances such as water, oxygen, and chlorides. Furthermore, the alkaline atmosphere of concrete acts as a passive shield on the steel bars, preventing

corrosion. Nevertheless, if the cover is insufficient or of a poor quality, it might contribute to increased permeability, allowing corrosive chemicals to reach the reinforcement more easily. As a result, a well-built concrete cover is critical in preventing corrosion.

3.3. Design Techniques' Influence

Berkowski and Kosior-Kazberuk (2017) has concluded as part of a case study that different design strategies can also have an impact on the corrosion of RC structures. For example, the design of water-draining details is critical to the durability of RC constructions. Poor drainage design can cause water to pool, increasing the risk of corrosion.

Furthermore, the design of elements such as joints, intersections, and corners can result in stress concentrations, which can lead to cracks and, thus, increased corrosion potential as indicated by Berkowski, Dmochowski and Kosior-Kazberuk (2013). Consequently, a good design should guarantee that these features are well-considered in order to reduce the danger of corrosion.

Wan-Wendner (2018), and Sadeghi, Musa and Nassrullah (2019) elaborated that modern design strategies, such as the use of corrosion-resistant reinforcement materials (e.g., stainless steel or epoxy-coated rebars) and advanced concrete technology (e.g., self-healing concrete, high-performance concrete), can also significantly reduce the hazard of corrosion.

2.5.5 Corrosion Impact on Reinforced Concrete Structures

Corrosion is a multidimensional challenges in reinforced concrete structures that affects their integrity, serviceability, and durability which was discussed by Mangat, Ojedokun and Lambert (2021), Chaudhari and Swamy (2022), and James et al. (2019), respectively. Eldeen and Nassar (2021) indicated that corrosion begins at the microscopic level and progresses to degrade overall structural performance over time. The same concept was endorsed by Shevtsov et al. (2022) as well.

It was indicated and elaborated by Bhagwat et al. (2022), Jeon et al. (2022) and Sharma et al. (2023) that corrosion in steel reinforcement bars (rebars) is caused by an electrochemical reaction that results in iron oxide or rust. In certain conditions, this corrosion product has a higher volume than the original steel. This increase in volume causes significant internal strains in the surrounding concrete. Due to the fact that concrete is weak in tension, these stresses surpass its tensile strength, resulting in visible manifestations of corrosion damage such as cracking and spalling - the flaking or peeling away of the concrete surface.

Liu et al. (2021) explained that cracking allows aggressive chemicals such as chlorides and carbon dioxide to infiltrate the concrete more easily, worsening the corrosion process and speeding the damage. Spalling and delamination (concrete layer separation) expose the reinforcing steel to the environment, causing even more corrosion. These physical damages diminish the structure's aesthetics as highlighted by (Goyal et al. 2018), but more crucially, they reduce the structure's load-bearing capability, posing dangers to structural safety and integrity as indicated by Ge and Kim (2021), Caprili et al. (2021) and Haris and Gadve (2022).

Furthermore, as corrosion develops, the effective cross-sectional area of the rebars diminishes as indicated and discussed by Haris and Gadve (2022). Because rebars' tensile strength is proportional to their cross-sectional area, corrosion directly reduces their ability to withstand tensile pressures. As a result, the structure's load-carrying capacity is jeopardized. Bossio, Lignola and Prota (2018) and Sato, Masuda and Kakegawa (2020) discussed the consequences of the corrosion and the safety problems that might arise, particularly in constructions with a high need for tensile strength or in seismic regions where the structure must withstand additional stresses. Ignoring such high safety risks might lead to a significant loss of lives. The collapse of Polcever viaduct in Genoa in 2018 and the Seongsu bridge in South Korea in 1994 represent an unfortunate example of lack of attention and consideration for the risk of corrosion where 43 and 32 people killed in these incidents, respectively (Duvnjak et al. 2021). Figure 12 below, shows different forms of corrosion impact on RC structures.

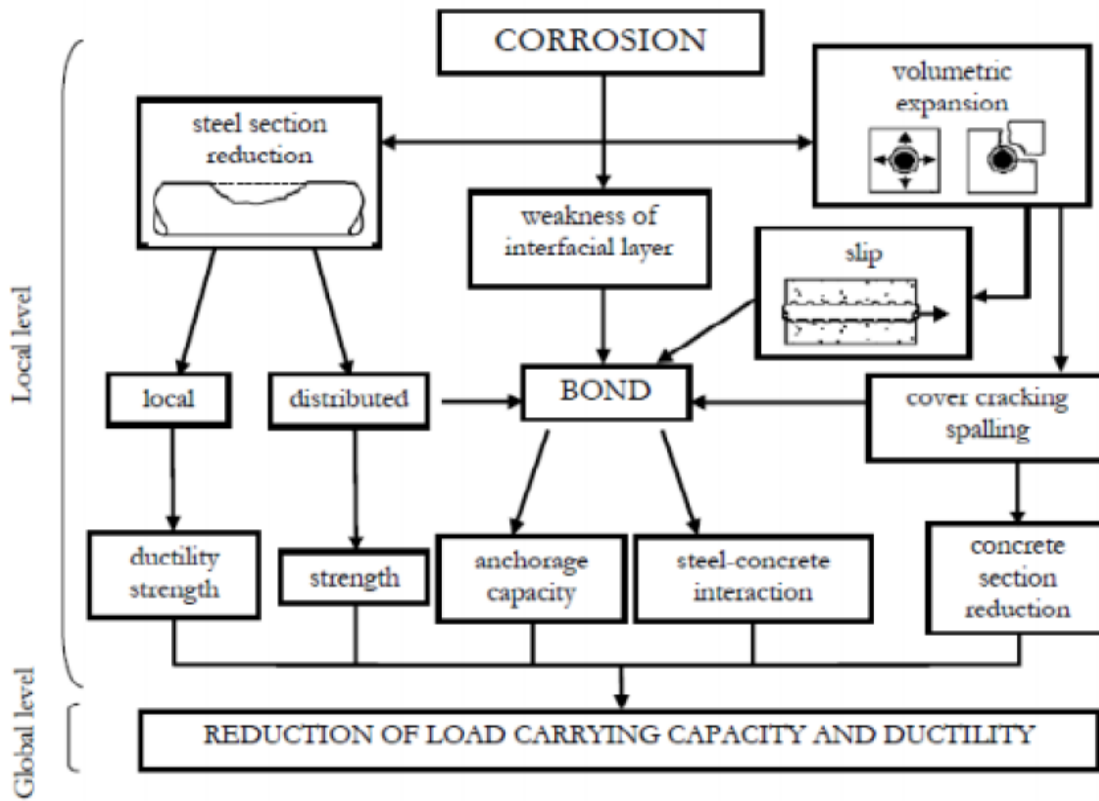


Figure 12: corrosion impact on RC structure (Sadeghi, Musa & Nassrullah 2019)

Corrosion has a significant economic impact on a global scale. The expense of inspecting, maintaining, repairing, and replacing corroded infrastructure represent a significant economic burden globally which is estimated to be close to USD 2.5 Trillion as indicated in Tamhane et al. (2022) work. Daniyal and Akhtar (2020) argued that it is not only the direct expenses of these activities that contribute to the overall economic burden, but also indirect costs such as operational downtime, loss of use, and potential liability issues.

Finally, corrosion accelerates the rate of deterioration of structures from a durability standpoint. It reduces the service life of the structure, typically demanding premature repair or replacement. This premature failure runs counter to the fundamental principle of sustainability since it consumes more resources, including materials, labor, and energy as discussed by Landa-Ruiz et al. (2021). When deteriorated structural components are dismantled and replaced, it also increases garbage output. Furthermore, García-Contreras et al. (2021) argued that the carbon footprint connected with the construction of concrete and

steel, as well as the environmental expenditures involved with the demolition and disposal of corroded structures, contribute to the environmental effect.

2.6 The Power of Early Detection and Proactiveness

2.6.1 The Role of Corrosion Monitoring Systems

Rao and Sasmal (2022) argued that because corrosion in RC structures occurs invisibly, continuous monitoring is critical for early diagnosis. Corrosion monitoring systems are intended to detect corrosion early on, well before apparent damage occurs. Song and Saraswathy (2007) presented similar idea, and highlighted those various procedures, including as electrical resistance, electrochemical techniques, ultrasonic testing, and half-cell potential measurements, that are used in these systems.

These systems are valuable in two ways as discussed by Taheri (2019) and Miró et al. (2021). For starters, they enable focused, proactive maintenance, prolonging structure lifespan while lowering overall repair costs. Second, they improve safety by preventing unexpected structural breakdowns. Monitoring corrosion allows structural engineers to spot early indicators of trouble and prepare appropriate treatments, saving catastrophic failures and loss of life.

Furthermore, corrosion monitoring devices aid in the design of future constructions. These devices enable engineers to make data-driven judgments on the durability and cost-efficiency of future RC structures by giving critical data on corrosion rates and the competence of various preventative measures. The significance of these monitoring devices was articulated by Arya and Dhanya (2021) and Ben Seghier, Keshtegar and Mahmoud (2021).

2.6.2 Early Detection: An Important Aspect of Infrastructure Management

While the significance of corrosion monitoring systems is obvious, their effectiveness is dependent on early detection which was elaborated by Roberge (2008) and Martínez Ibernón et al. (2022). Detecting corrosion early enables for timely corrective actions that can halt or delay the corrosion process, specially, in critical zones. Late detection, on the other hand, frequently needs extensive repairs or even total replacement of the structure, resulting in significant expenses and interruptions.

García-Contreras et al. (2021) and Martínez Ibernón et al. (2022) argued that, not only early identification also allows for a fuller understanding of the corrosion process, allowing for a more accurate assessment of the structure's remaining service life, but also, it enables engineers to identify and correct problematic corrosion sources such as insufficient concrete cover, poor-quality concrete, or excessive exposure to corrosive substances.

2.7 Corrosion Monitoring Solutions:

Due to its importance, the literature has a versatile and wide range of articles that describes different aspects of the corrosion monitoring systems in RC structure content. It varies from a quick overview of multiple systems per article to a deep dive into one specific technique/solution.

According to Kaur and Saxena (2023), corrosion monitoring systems for RC structures can be classified into either destructive systems or non-destructive systems. The focus in the recent literature is on the non-destructive methods due to its fundamental advantage of not causing damaging to the sample under testing whether on site or in lab as articulated by Daniyal and Akhtar (2020) and many others. Furthermore, non-destructive corrosion monitoring method is a large family of methods that can be sorted out into multiple categories that are designed around the theoretical concepts of these systems. Zaki et al. (2015), Gholizadeh (2016), and Hassani and Dackermann (2023) and many others elaborated that non-destructive monitoring methods can be categorised into a minimum of 6 categories as shown in the below in figure 13:

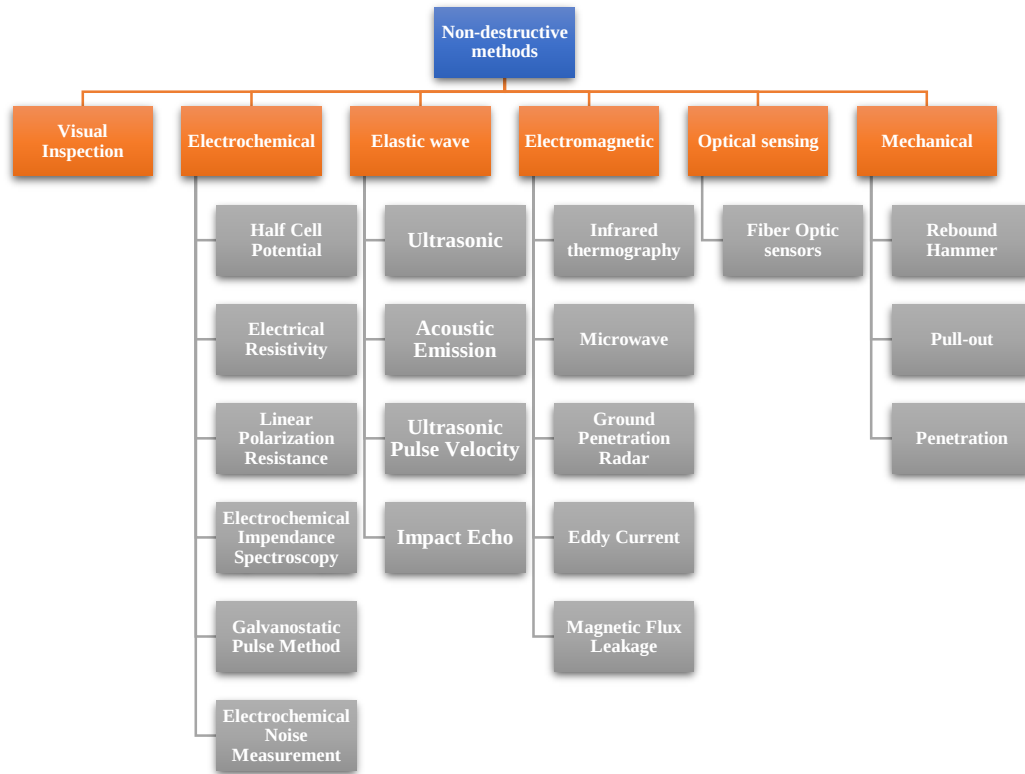


Figure 13: non-destructive corrosion monitoring

After careful review to the available and accessible literature, the subcategories shown in figure 13 were selected to be covered under this review.

2.7.1 Visual Inspection:

Visual examinations have long been used to monitor corrosion in Reinforced Concrete (RC) buildings. This conventional and periodic method entails a thorough examination of surface anomalies such as staining, cracking, and spalling, which are indicative of probable corrosion in the building's reinforcement. Visual inspection's virtues are its simplicity and directness, generally requiring no complicated tools and providing instant insights regarding surface degradation (Song & Saraswathy 2007). However, Zaki et al. (2015) argued that visual inspection depends on the level of expertise that inspector has and its main drawback is the inability to detect hidden, subsurface corrosion, which can silently compromise the structural integrity of RC buildings. While visual inspections can detect visible symptoms of corrosion as shown in figure 14 below, they may miss hidden damage until it shows on

the surface, which is often at an advanced level. Additionally, Duvnjak et al. (2021) argued that to have proper visual inspection, the damaged location or location under investigation has to be accessible.

Recent technological breakthroughs have arisen to supplement traditional visual inspections in order to overcome these constraints. Though just briefly mentioned, high-resolution cameras provide a level of detail that exceeds that of the human eye (Komary et al. 2023). Robotics technology is extending inspection reach into inaccessible or hazardous regions (Pfändler et al. 2019), while drones are giving a hitherto unseen overhead perspective for huge and high-rise structures (Komary et al. 2023).

Though these technologies offer eye-catching solutions, they are not intended to replace traditional visual inspection, but rather to augment it. The combination of human skills and technical technologies results in a more robust and complete approach to corrosion monitoring. This mix of old and new is critical to sustaining and protecting the durability and safety of RC buildings (Negi et al. 2023).



Figure 14: visual inspection site work (Zaki, Murdiansyah & Jusman 2021)

2.7.2 Electrochemical Methods:

1. Half-cell Potential Measurement (Open Circuit Potential Measurements):

The measurement of half-cell potential (HCP) has evolved as a non-destructive and cost-effective compared to other electrochemical methods as argued by Fan and Shi (2022) as a method for monitoring the risk of corrosion on RC structures.

The half-cell potential measurement approach is based on the basic electrochemical nature of corrosion. To evaluate the potential variance between the electrode and the reinforcing steel, a reference electrode, typically constructed of copper/copper sulfate (Cu/CuSO₄), saturated calomel, or silver/silver chloride (Ag/AgCl), is used in conjunction with a voltmeter. The half-cell potential values that result indicate the possibility of corrosion action as described by Taheri (2019), Cavalcante et al. (2020), Daniyal and Akhtar (2020) and others.

Anand et al. (2021) and Chaudhari and Swamy (2022) explained that Half-cell potential readings are captured by connecting the reference electrode to the voltmeter and placing it on the concrete surface as shown in figure 15. The reinforcing steel is linked to the voltmeter's other terminal. The potential difference is then recorded at various sites across the structure, resulting in the formation of a potential map. A higher negative potential indicates a greater possibility of corrosion activity. ASTM C876 gives interpretation recommendations for certain potential measurements. A potential less than -200 mV (vs. Cu/CuSO₄) generally implies a low likelihood of corrosion, whereas a potential greater than -350 mV indicates a significant likelihood as elaborated in table 1 below. Figure 16 shows on site HCP measurement.

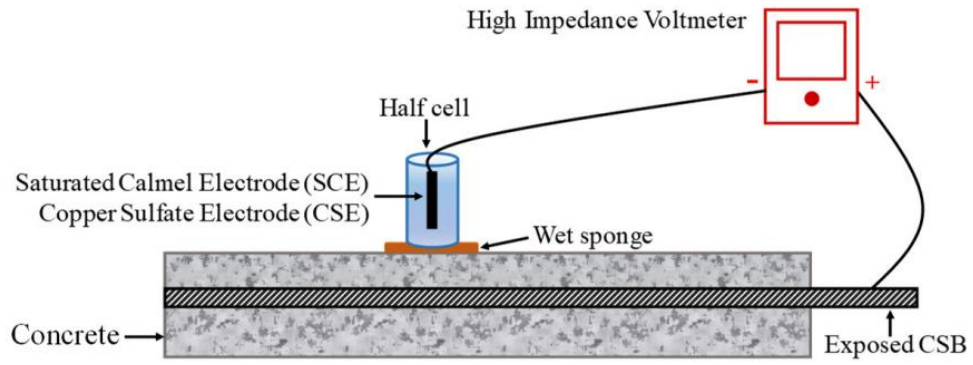


Figure 15: HCP Schematic(Luo et al. 2018)

Table 1: corrosion evaluation using HCP (Anand et al. 2021; Chaudhari & Swamy 2022)

S.N.	HCP	Corrosion Potential (%)	Observations
1	Less than -35V	>90	Corrosion is progressing at the time of the test
2	-20 to -35V	50% (not confirmed)	No certainty about the status of corrosion
3	Higher than -20V	<10	No corrosion at the time of the test

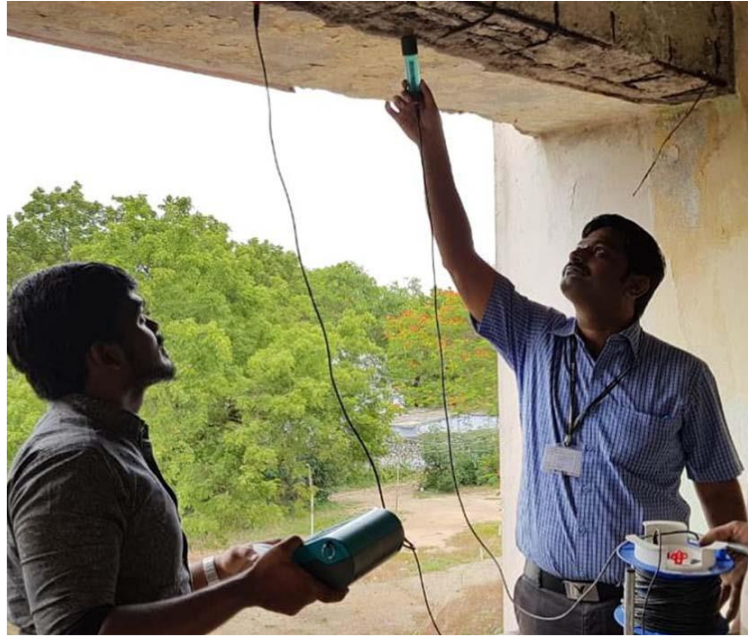


Figure 16: HCP in action (Anand et al. 2021)

2. Electrical resistivity:

From an electrical engineering perspective, electrical resistivity is a material attribute that determines how strongly a material opposes or resists the flow of electric current. However, from a structural engineering perspective, the electrical resistivity is an important characteristic of the concrete that would have an indicative information about its quality and durability (Cheytani & Chan 2021). As elaborated by Michael, Kennedy and Oba (2021), electrical resistivity (ER) value is linked to the reinforced concrete raw materials characteristics as well as environmental factors such as humidity, temperature and chloride concentration. Shevtsov et al. (2022) argued that a high resistivity suggests that there are few conductive ions present, lowering the potential of steel corrosion. A low resistivity, on the other hand, indicates a higher probability of corrosion due to the increased availability of conductive ions.

The literature described multiple methods for RC ER measurement. However, Wenner Probe method is well cited and employed in the field as well as the literature, as highlighted by Robles, Yee and Kee (2022) in their detailed study for the ER technique. The four-point Wenner Probe arrangement, commonly known as the Wenner Probe method (WPM), is carried out by inserting four probes in a linear and equidistant pattern, as shown in Figure 17. The input current is injected at the two

outside electrodes in this arrangement, and the electrical potential variance is recorded at the remaining two inner electrodes (Daniyal & Akhtar 2020; Robles, Yee & Kee 2022).

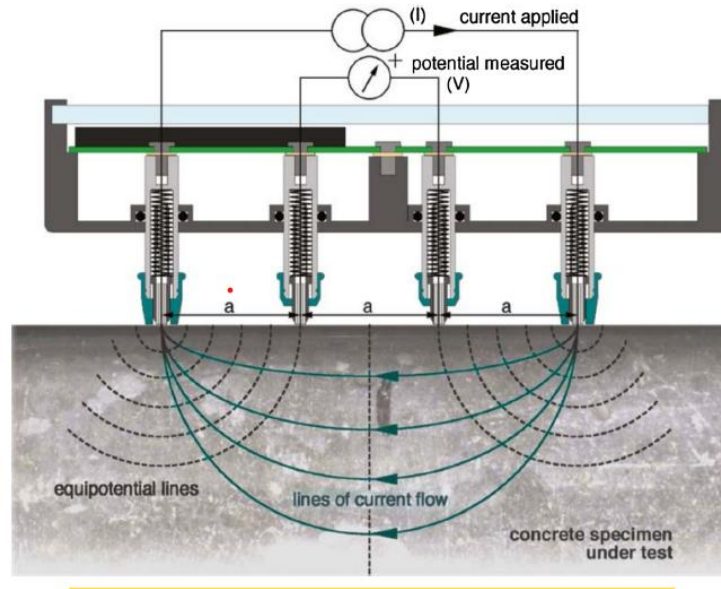


Figure 17: Schematic of Four-point Wenner probe (Cheytani & Chan 2021)

3. Linear Polarization Resistance:

Pagadala, Mundra and Bansal (2022) elaborated that the LPR method is based on electrochemical principles. It measures polarization resistance, which is the resistance to current flow caused by a slight change in the electrode potential near the open-circuit potential. Based on the Stern-Geary equation, the corrosion rate can be approximated from the measured polarization resistance.

As explained by Shevtsov et al. (2022) the measurement is carried out using a three-electrode cell: the steel reinforcement serves as the working electrode in the setting of an RC construction, while a reference electrode is put in the concrete and the third one is usually a stainless-steel auxiliary electrode as shown in figure 18 below. Daniyal and Akhtar (2020) explained that the LPR approach involves introducing a minor potential difference (typically 10 – 30 mV) around the corrosion potential and measuring the subsequent current flow. The ratio of the applied voltage change to the corresponding current change (E/I) yields the polarization resistance (R_p).

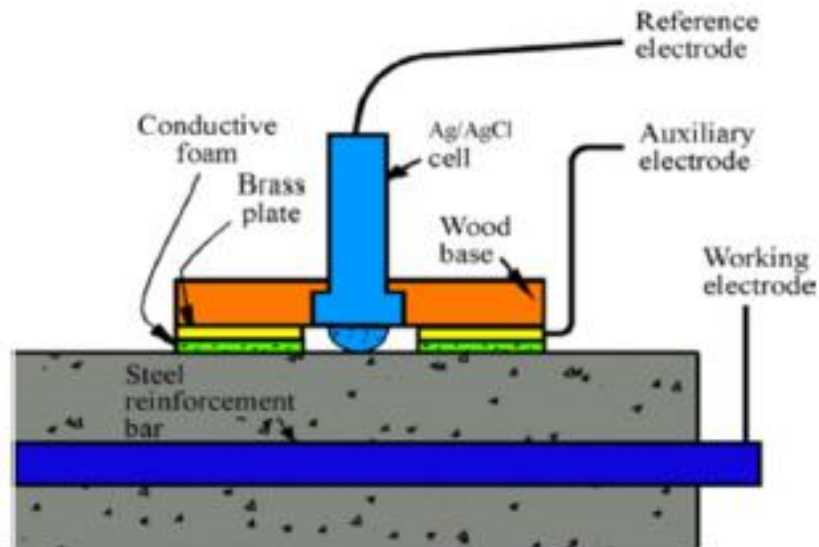


Figure 18: LPR Measurement (Nikoo, Sadowski & Nikoo 2017)

Daniyal and Akhtar (2020) articulated that the rate of corrosion is proportional to the polarization resistance. As a result, a high R_p number indicates a gradual corrosion rate, whereas a low R_p value indicates a fast corrosion rate. The data obtained offers a real-time measure of the rate of steel corrosion and can be used as an early warning signal of harmful corrosion activity. Typical corrosion criteria of RC structure is detailed in table 2 below.

Table 2: LPR vs Corrosion

Corrosion Indication	Polarization resistance ($K\Omega cm^2$)	Current density ($\mu A/cm^2$)	Corrosion Penetration ($\mu m/ year$)
Very high	2.5-0.25	10-100	100-1000
High	25-2.5	1-10	10-100
Low/Moderate	250 – 25	0.1 – 1	1-10
Passive	>250	<0.1	<1

4. Electrochemical Impedance Spectroscopy:

Electrochemical Impedance Spectroscopy (EIS) or Alternative Current (AC) Impedance Spectroscopy (ACIS) is a versatile electrochemical technique that provides insights into the corrosion mechanisms that occur in RC structures (Rajendran et al. 2023). As explained by Okenyi and Alawode (2021), it works by applying an oscillating potential of about 10-20mV or current to an electrode/electrolyte system and then measuring the response signal. Corrosion processes can be better understood by analysing the complex impedance using the Fourier transforms as indicated by Hallemans et al. (2023), and represent it in an equivalent circuit (Randels circuit). Daniyal and Akhtar (2020) elaborated that the Randels circuit is made up of a resistance R_c connected in series to a loop with a separate resistance R_{ct} and a capacitance C_{dl} connected in parallel. The R_c value denotes the resistance of the concrete pore electrolyte or the resistance of the concrete cover. The charge transfer resistance at the steel surface represents the ease with which charged ions can leave the steel surface and reach the electrolyte (i.e. metal dissolution resistance). The C_{dl} is a double layer capacitor, referring to the formation of two layers on the steel/electrolyte interface. The first layer is created due to the attraction of molecules to the anions (free electrons) on the steel surface. The second layer is created as a result of molecules' attraction to cations in the pore solution. Furthermore, R_{ct} and C_{dl} are both similar to the ionic resistance of the corrosion products film formed on the steel surface. As shown in figure 19 and 20.

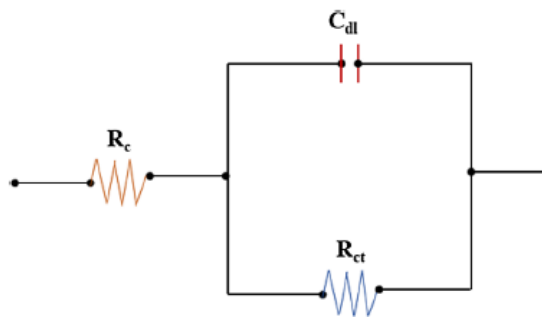


Figure 19: Randels circuit (Daniyal & Akhtar 2020)

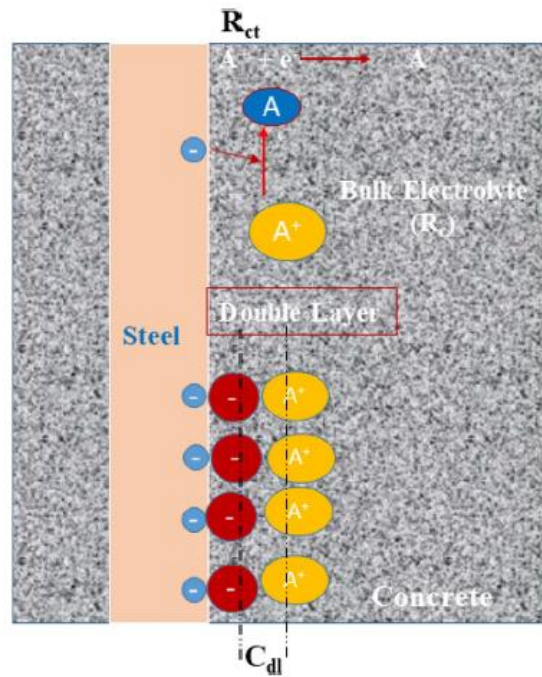


Figure 20: Impedance components in steel concrete interface (Daniyal & Akhtar 2020)

Using Randels circuit, different graphs can be generated: the Bode plot (AC frequency, phase and amplitude) which would give an understanding for the material phase and the changes in the magnitude under different frequency levels, and the Nyquist plot (Rajendran et al. 2023). Pagadala, Mundra and Bansal (2022) explained that Nyquist plot which is a vector plot that is plotted between Z real and Z imaginary, resulting in a semi-circular plot from which the concrete cover/ electrolyte resistance (R_Ω), R_{ct} , and C_{dl} can be calculated. As articulated by Daniyal and Akhtar (2020), in the Nyquist plot, the diameter of the extrapolated semicircle represents the charge transfer resistance (R_{ct}), which is identical to the real polarization resistance. Thus, the bigger semicircle's diameter is, the higher the polarization resistance is and the lower the corrosion rate is and vice versa. Figure 21 below shows the two plots.

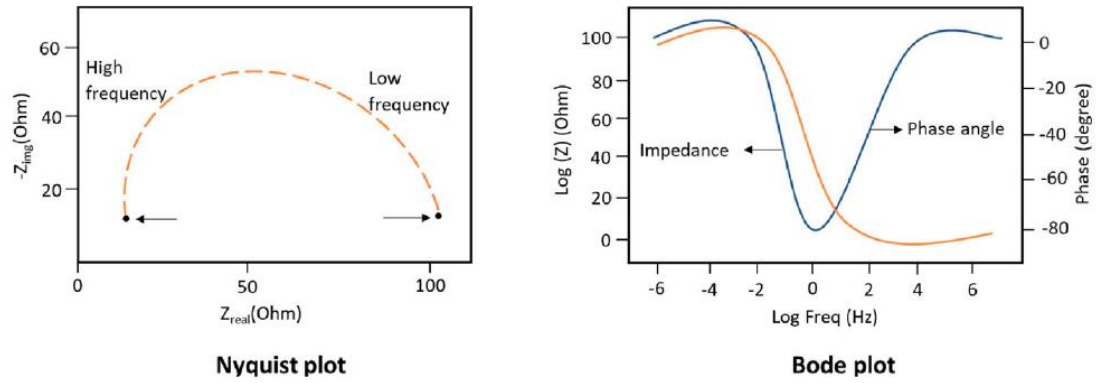


Figure 21: EIS plots (Rajendran et al. 2023)

5. The Galvanostatic Pulse Method (GPM):

The galvanostatic pulse method is a non-destructive testing method that includes passing a current pulse through a structure and measuring the response voltage decrease over time (Zaki et al. 2015). This method works by passing a steady current pulse through the reinforcing steel (The literature showed different ranges of the current to be applied which varies from (5 - 400 μ A) for up to 10 seconds (Frølund, Jensen & Bassler 2002) to (10-20 μ A) for 8-10 seconds (Figueira 2017)) and detecting the potential degradation after the pulse is turned off. System schematic is shown in figure 22 below. As explained by Raczkiwicz and Wójcicki (2020) The curve obtained from this test using Randles circuit allows the corrosion rate, polarization resistance, and concrete resistivity to be calculated.

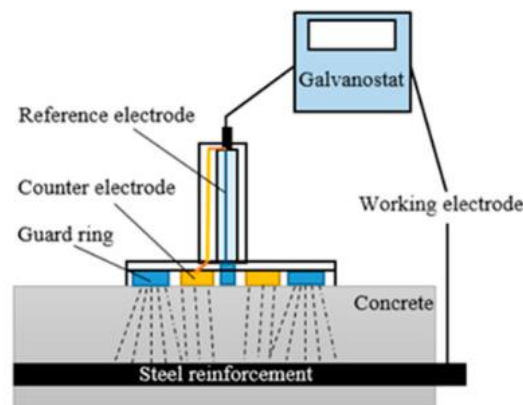


Figure 22: galvanostatic pulse method schematic(Zaki et al. 2015)

6. Electrochemical Noise Measurement (ENM):

Fukuyama, Nagai and Noguchi (2009) explained that by measuring and analysing the EN of electrodes exposed to a medium, the system's uniform corrosion rate or sensitivity to localized corrosion can be estimated using the EN method. The term "EN" describes a phenomenon in which the oxidation-reduction reaction on the electrode surfaces causes the average anodic or cathodic current of electrodes to fluctuate. The term "EN" also refers to the phenomena where electrode corrosion potential varies as a result of such current vibration. Both intermittent and constant noise might be heard in a corroded system. Sporadic noise is related to non-periodic fluctuation, such as abrupt acceleration/deceleration of response, and results from the beginning/ending of pitting corrosion and the propagation of stress corrosion cracking. Continuous noise is a representation of the information relating to slow changes in a physical system brought about by slow, long-lasting fluctuations or continuous, tiny variations. Sample of ENM connection schematic is shown in figure 23 below.

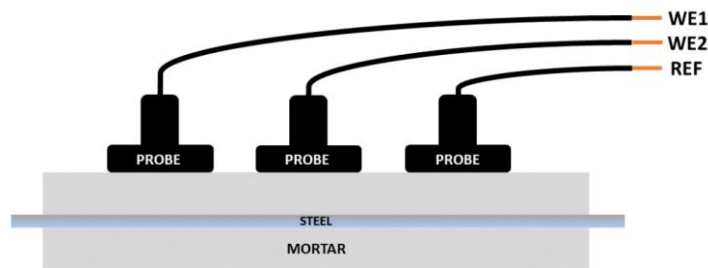


Figure 23: ENM connection schematic (Mills, Lambert & Yang 2021)

Ma et al. (2019) elaborated that among the EN test modes are apotentiostatic, which only collects electrochemical current noise (ECN), galvanostatic, which only collects electrochemical potential noise (EPN), and zero resistance ammeter (ZRA), which simultaneously collects EPN and ECN.

2.7.3 Elastic Waves Methods:

1. Ultrasonic Testing (UT):

Ultrasonic testing is based on the idea that faults or changes in a material's qualities can be found by sending high-frequency sound waves through it that are above the range of human

hearing (Shevtsov et al. 2022). Ultrasonic waves are normally produced by a transducer in the testing apparatus. Miró et al. (2021), Amiri, Erdogmus and Richter-Egger (2021) and others explained that these waves are reflected and picked up by the receiver in the transducer when they encounter a break in the route or a change (like corrosion). The waves travel time, and its amplitude provides information about the depth of the fault or defect, making corrosion easier to find and assess. For example, in RC structure, an increase in the recorded amplitude values denotes the beginning of corrosion. However, Liu et al. (2016) and Amiri, Erdogmus and Richter-Egger (2021) argued that the amplitude readings were found to be more sensitive compared to time readings and easier to analyse and interpret.

Amiri, Erdogmus and Richter-Egger (2021) clarified that the UT transducer is applied to the concrete's surface by technicians, and sound waves travel through the concrete and into the steel reinforcement as shown in figure 24. Technicians can detect and monitor concrete flaws including voids and cracks as small as 0.2mm as well as the thickness of the concrete cover and the location of rebars. Amiri, Erdogmus and Richter-Egger (2021) highlighted in their work that, based on many studies they referenced, lower ultrasonic frequencies employed in RC structures studies showed better performance (Marcantonio et al. 2019).

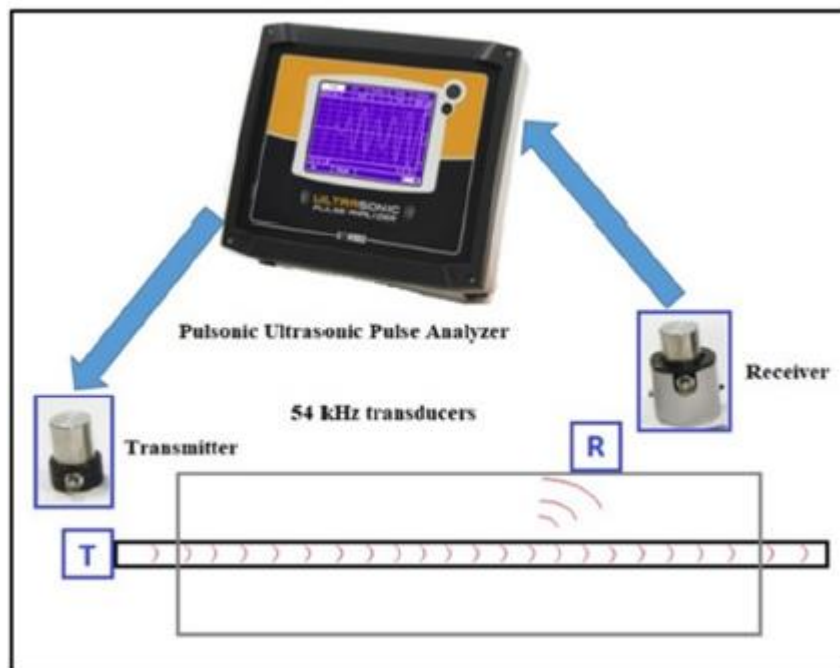


Figure 24: UT arrangement(Amiri, Erdogmus & Richter-Egger 2021)

2. Acoustic Emission (AE):

The theory behind acoustic emission is the detection and analysis of stress waves that are produced in a material as a result of changes to its internal structure. These changes could be brought on by mechanisms including corrosion, crack formation, dislocation movements,...etc (Li et al. 2020). Abarkane et al. (2023) explained that piezoelectric sensors linked to the material's surface can pick up on these stress waves as they go through the material. (Majhi et al. 2022) clarified that the collected AE signals can be further examined to deduce details about the emission source, such as its location, size, and type of damage mechanism.

Majhi et al. (2022) elaborated that as a passive technique for monitoring corrosion, acoustic transducers can be put on concrete building. According to earlier studies, corrosion generates acoustic activity between 20 and 80 kHz (Verstrynge et al. 2022). These acoustic waves' signal analysis has revealed several aspects, including the emergence of microcracks, the propagation of isolated cracks, and the debonding of the reinforcing steel during corrosion. As a result, sonic activity has been linked to the timing of corrosion beginning and the initiation of concrete cracking during corrosion (Van Steen & Verstrynge 2021). Verstrynge et al. (2022) has discussed multiple methods for analysing the AE signal based on which it is worth highlighting that the analysis method is controlled by the research choice and aim, i.e. there is no right and wrong in this regard. General schematic for AE system is shown in figure 25.

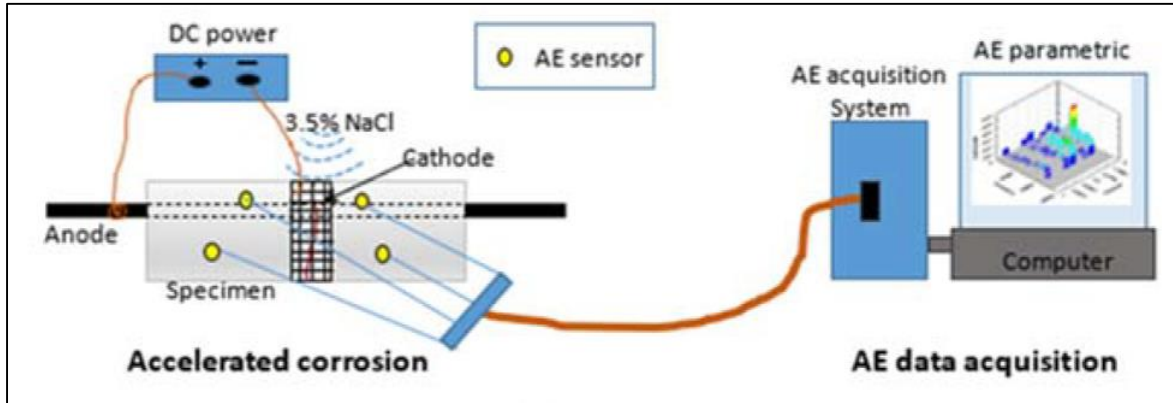


Figure 25: AE schematic(Majhi et al. 2022)

3. Ultrasonic Pulse Velocity Test (UPV):

Mukhti et al. (2023) elaborated that UPV is an investigation method that examines the speed at which ultrasonic waves move through a substance. The technique uses transducers to create and receive ultrasonic pulses in the setting of reinforced concrete structures, recording the time it takes for these pulses to travel a predetermined path. Critical information about the density, homogeneity, and general quality of the material can be gleaned from the speed of these pulses(Ndagi et al. 2019).

Furthermore, Concha and Oreta (2019) clarified that the sensitivity of UPV to changes in the physical characteristics of the concrete structure, particularly the concrete's compressive strength and density, underlies its usefulness in corrosion monitoring. Concrete can fracture and spall when steel reinforcing corrodes because it expands and raises internal stresses. The propagation velocity of ultrasonic pulses is greatly impacted by these changes in the microstructure of the concrete. As a result, higher velocities suggest that the concrete is of superior quality, homogeneous, dense, and continuous, whereas slower velocities can suggest that the concrete has fractures and voids. Additionally, as argued by Liu et al. (2022), UPV is helpful for spotting corrosion's early stages. Physical evidence of corrosion typically doesn't appear until the process has advanced substantially. The UPV method, on the other hand, can spot changes in the internal structure of the concrete far earlier, even before obvious cracking or spalling takes place(Concha & Oreta 2019). Early detection enables the

adoption of preventative measures, which can significantly extend the structure's lifespan and lower the price of structural repairs. Figure 26 below shows UPV test setup.



Figure 26: UPV test setup (Bolborea et al. 2021)

To perform this test, Ndagi et al. (2019) elaborated that transducers are available with a variety of frequencies depending on the intended application and the type of concrete material to be evaluated. According to him, using a transducer with a high frequency, namely one over 100 kHz, is best for concrete samples that are short in length. In contrast, using a low-frequency transducer, specifically one with a frequency of 25 kHz, is best for larger concrete samples or samples that are lengthy in length. In addition, using transducers with frequencies between 50 kHz and 60 kHz even though higher frequency waves tend to have better spectra at the point of propagation because they are more easily degraded as they move along compared to low frequency waves (Mukhti et al. 2023). In literature, there are multiple recommendation for the frequency range to be used. Nevertheless, as summarised by (Ndagi et al. 2019), ACI has identify nominal values for the natural frequencies of transducers for different path length as shown in table 3 below:

Table 3: ACI Frequency Recommendation

Path length (mm)	Natural frequency of transducer (kHz)	Min. transverse dimensions of members (mm)
Up to 500	150	25
500 - 700	> 60	70
700 - 1500	> 40	150
Above 1500	> 20	300

On the other hand, Nanayakkara, Najm and Sabri (2022) argued that the results of UPV are affected by several variables, including temperature, moisture content, path length, specimen form and size, steel fibre, and reinforcing bars.

4. Impact Echo (IE):

Alhawati, Khan and Ashour (2020) elaborated that Impact Echo is a resonant method for inspecting concrete constructions for defects, cracks, or corrosion. It functions according to the wave propagation and reflection theory. In essence, a structure's surface is subjected to a short-duration stress pulse. A sequence of echo signals is produced as a result of the stress waves' propagation through the structure, reflection off walls or other obstructions (such as sound and damaged concrete) and return to the surface. One can find structural anomalies like corrosion, delamination, or vacancies by performing a frequency domain analysis on these signals. Furthermore, Zhang, Yan and Cui (2016) and others discussed that traditionally, IE testing relies on the fast Fourier transform (FFT) approach to convert time domain waveforms into frequency spectra and deduce internal conditions by locating the peak frequency within the frequency spectrum. Additionally, Scherr and Grosse (2021) clarified that low frequency flexural vibrations that represent the out-of-plane vibration of the delaminated section dominate the frequency spectrum and indicate damage in a delaminated plate, depending on the depth of the defect. Low frequency, infrequent flexural vibrations indicate superficial faults, while frequencies greater than the IE frequency indicate deep-lying defects. The measured frequency relates to the depth of the defect. Moreover, the smallest delamination size that can be detected is determined by the width-to-depth ratio, where the defect width should be five times greater than the depth of the defect. However,

Liu et al. (2019) argued that the accuracy and efficiency of the IE test might be affected by a number of factors. This includes the type of material used in the construction, the size and shape of the defect, the concrete element's thickness. EI schematic is shown in figure 27.

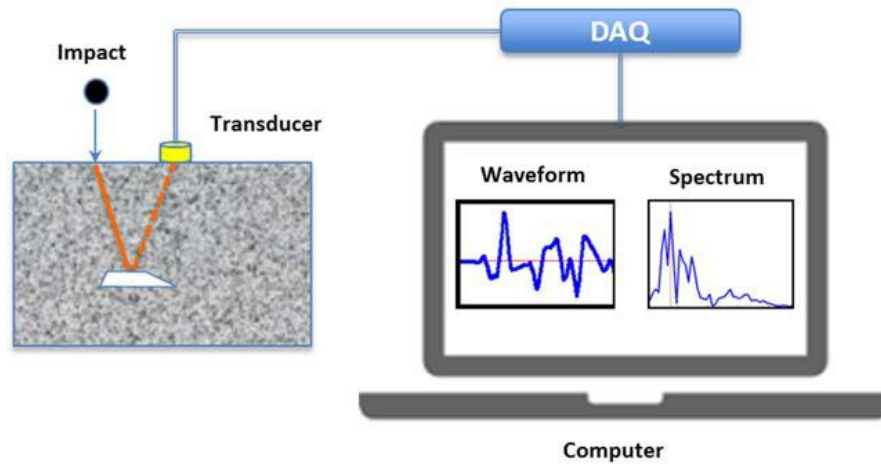


Figure 27: IE schematic(Zhang, Yan & Cui 2016)

2.7.4 Electromagnetic Methods:

1. Infrared Thermography (IRT):

Infrared is an electromagnetic wave whose wavelength is between 0.8 and 1000 meters. Between microwaves and visible light (Na & Paik 2019). Kot et al. (2021) articulated that IRT is a non-contact NDT method that examines and detects thermal patterns on a surface using the principles of infrared radiation. The amount of infrared radiation that any material emits depends on how hot it is. However, as suggested by Ichi and Dorafshan (2022) Infrared radiation is produced by objects that are warmer than absolute zero (-273.15° Celsius or 0 Kelvin). Furthermore, Li, Zhou and Ou (2021) clarified that when this radiation is detected and captured by an infrared camera, it can be processed to create thermal images or thermograms by being converted into electrical signals. Through colour or grayscale patterns, these images discriminate between various temperatures and, consequently, between various materials or states of materials as explained by Ichi and Dorafshan (2022).

Abu Dabous and Feroz (2020) elaborated that IRT determines the temperature gradient of concrete surfaces when exposed to natural or artificial heat. Due to their poorer thermal conductivity than concrete, concrete delamination interrupts heat transport. As a result, sections above delamination appear hotter than similar portions above sound concrete. There are two types of IRT procedures used: Thermography, both active and passive. Kannan, Manoharan and Venkataraman (2015) articulated that thermography that operates in two wavelength ranges, 3-5 m (SWIR) and 8-12 m (LWIR), is known as passive, steady state, or static thermography. In essence, passive thermography is based on analysis in which temperature gradients on the test specimen's surface are not excited by any external excitation (Wu et al. 2021). Ichi and Dorafshan (2022) argued that this method is more suitable to be employed when the specimen is a large structure.

Kannan, Manoharan and Venkataraman (2015) elaborated that thermography that is active or dynamic relies on the detection and documentation of thermal IR radiations generated by the object surfaces using an infrared camera as shown in figure 28 below. Wu et al. (2021) suggested that to perform an IRT test, an external energy source must be employed to provide a thermal difference between the observed specimen and the feature of interest (subsurface flaws).

IRT test environment plays a crucial role in the success of the test. Ichi and Dorafshan (2022) argued that a structure's surface temperature can be changed by wind speed, solar radiation, and ambient temperature, which can affect IRT results. Furthermore, Zheng et al. (2022) concluded in their study that surface coatings, concrete surface roughness, and colour can all have an impact on a material's emissivity and heat transport properties, which can then alter thermal imaging. Moreover, Wu et al. (2021) suggested that corrosion depth and size should be considered as a major factor as well. IRT detection may not be able to distinguish a thermal contrast for early-stage corrosion or corrosion at a large depth.



Figure 28: active IRT experiment setup(Zheng et al. 2022)

2. Microwave Thermography (MWT):

The frequency range for microwave thermography is between 300 MHz and 300 GHz (Wu et al. 2021). May, Alam and Nayan (2022) elaborated that dielectric coating materials are easily penetrated by microwaves (MW) without experiencing much attenuation, allowing interior structures to interact with the microwave data. However, microwaves signals do not have the same behaviour with all materials. As argued by Keo et al. (2022), MW penetration depth has a dependency of a material characteristics called dielectric constant. As discussed

by May, Alam and Nayan (2022), Keo et al. (2022) and others, the change of materials characteristics between concrete covers, corrosion, flaws and rebars provide more information about the structure of the subject under testing like concrete cover thickness and corrosion existence.

Wu et al. (2021) clarified that when using microwave NDT procedures, the specimen is measured for transmitted or reflected microwave signals, and their magnitude or phase is examined. On the other hand, Farhangdoust and Mehrabi (2019) argued that it takes skill to interpret the data of microwave thermography. For example, for the purpose of evaluating pit dimensions, a high-resolution image can be created using the variance in the phase and magnitude of reflected signals that can be interpreted by an experienced engineer/operator to identify the pit dimensions. Li et al.(2023) discussed the influence of concrete parameters, lift-off and the frequency of operation during inspection and conclude that lift-off and frequency are important factors affecting the reflection and transmission qualities. However, concrete parameters have a minor impact which can be ignored.

Wu et al. (2021) detailed that for a typical lab test to be performed, a waveguide probe with a particular lift-off is often positioned above the test sample. Excitation signals are generated, and the frequency spectrum of the reflected signals is recorded using a vector network analyser. After that, this information is sent across a General Purpose Interface Bus (GPIB) to a controlling PC. A parallel port connects an X-Y scanner to a controller, which the PC uses to control it as shown in figure 29 below.

Gkantou et al. (2019) articulated that engineers are now able to generate more precise fault models for elements and improve the results of their non-destructive evaluation thanks to recent advancements in software. In the same context, Farhangdoust and Mehrabi (2019) argued that three-dimensional view is now possible where the single scanned signals can be stacked one on top of the other to produce two-dimensional images, while numerous scans of the elements in various directions can be combined to produce three-dimensional views which would provide a great assist.

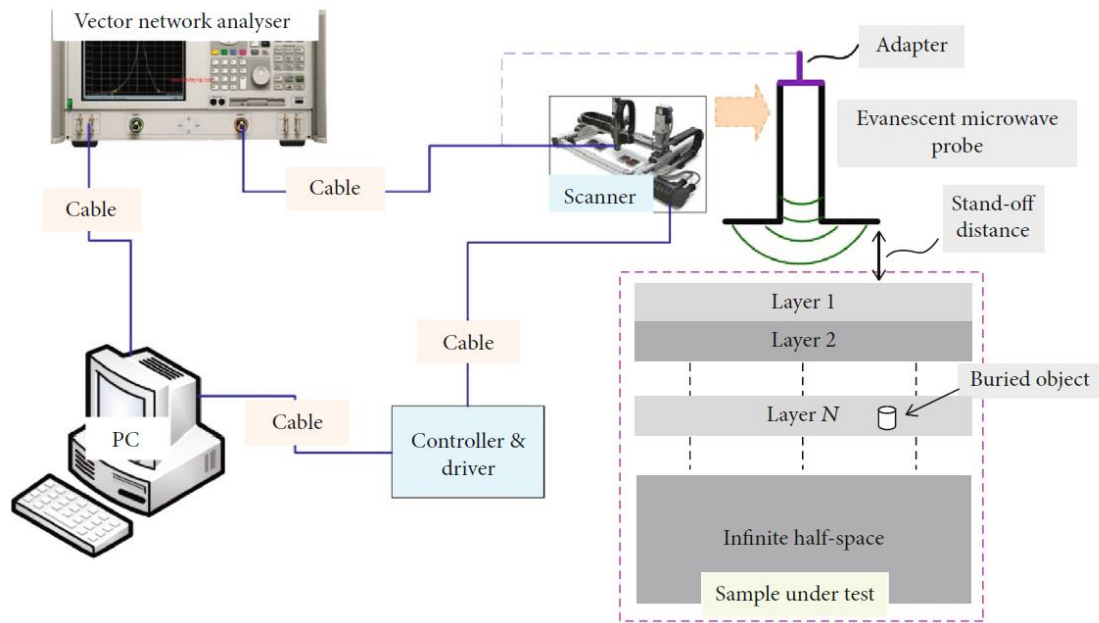


Figure 29: MW lab test setup (Wu et al. 2021)

3. Ground Penetrating Radar (GPR):

Ground Penetrating Radar is another NDT testing method that works by emitting radio waves into the ground and then detecting the returned signals. Tesic et al. (2022) articulated that the reflected waves can disclose information about the inner structure of the material, such as the placement of rebars and the state of the concrete and rebars.

Manhães et al. (2021) described the process clarifying that GPR generates and detects critical electromagnetic fields by applying an impulse to an antenna located near the ground. The GPR transmitter antenna converts the excitation voltage into a predictable temporally and geographically distributed field, while the receiving antenna detects and converts the temporal variation of an EM field vector component into a recordable signal. During an examination, a GPR transmitter sends an electromagnetic pulse source into the ground via an antenna. When this pulse encounters a barrier between materials with varying dielectric permittivity, it is partially reflected or refracted back to the surface, where a receiving antenna records the magnitude and arrival time of the returned pulse.

Zaki et al. (2018) elaborated that because radio waves are affected by changes in the conductivity and permittivity of the material - properties that might change owing to

corrosion - the nature of these reflections can assist identify areas of corrosion. Álvarez, Hernández Martín and Carraz Hernández (2023) elucidated that if the amplitude of the reflected wave increases, the corrosion zone is said to be in the active stage of corrosion; if it decreases, the corrosion zone is in the early stage. In addition, wetlands' distinctive sound and low signal intensity values are correlated with polarity variations of high amplitude waves. Figure 30 below shows a GPR test schematic.

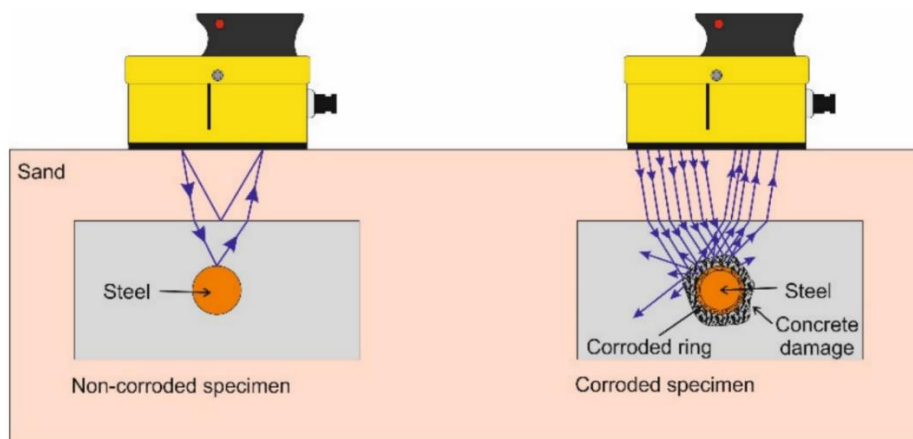


Figure 30: GPR schematic (Sossa et al. 2019)

4. Eddy Current Testing (ECT):

Eddy current testing is a non-destructive testing method that detects and characterizes surface and subsurface faults in conductive materials using electromagnetic induction (Ha, Lee & Lee 2021). May, Alam and Nayan (2022) elaborated that this method operates by creating eddy currents in the material being tested; these currents generate a magnetic field that opposes the original field. Any variations in the phase and magnitude of these currents caused by flaws or corrosion will cause the magnetic field to fluctuate, which may then be detected and analysed. As indicated by Daura (2022), ECT can be used for crack quantification, thickness identification, and coating permeability and conductivity measurements.

Hassani and Dackermann (2023) articulated that a probe is placed near the surface of the structure as part of the method. This probe has a coil that produces an alternating magnetic

field. Within the material under test, this field produces eddy currents to flow in a closed loop. The reinforcing bars (rebars) are the major conductors for these currents in an RC construction. The eddy current field is unaffected if there is no defect or corrosion. The presence of corrosion or flaws, on the other hand, affects the passage of these currents and introduce changes in the conductivity and permeability, which will result in modifying the magnetic field. These changes are detected by the probe and interpreted by the operator, or the monitoring system as explained by Ha, Lee and Lee (2021).

In their work, de Alcantara et al. (2015) described an effective methodology for using ECT to identify corrosion processes in concrete structural reinforcement: First, measurements can be taken over the reinforcement's uncorroded areas. This will enable the determination of the gauge and concrete cover (if known). Following that, measurements along the reinforcement can be done consecutively, with the outcomes compared to those for the non-corroded areas. Figure 31 below shows a lab test setup for ECT.



Figure 31: ECT lab test setup(de Alcantara et al. 2015)

5. Magnetic Flux Leakage (MFL):

Based on the concept of magnetic flux, which is a measurement of the total magnetic field that flows across a specific location, is Magnetic Flux Leakage. The magnetic field created by inducing a magnetic flux is evenly distributed in a perfect, uncorroded RC structure. The regularity is disrupted if the rebar inside the structure corrodes, gets damaged, or has a microcrack though. The term "magnetic flux leakage" is used to describe these localized disruptions or modifications in the magnetic field. Monitoring these leaks can therefore be employed to determine the extent and position of corrosion within the RC structure as clarified by Li et al. (2023). Furthermore, Farhangdoust and Mehrabi (2019) discussed that the source of the magnetic field could be a permanent magnet or an electrically activated one. Figure 32 below shows a schematic for MFL test.

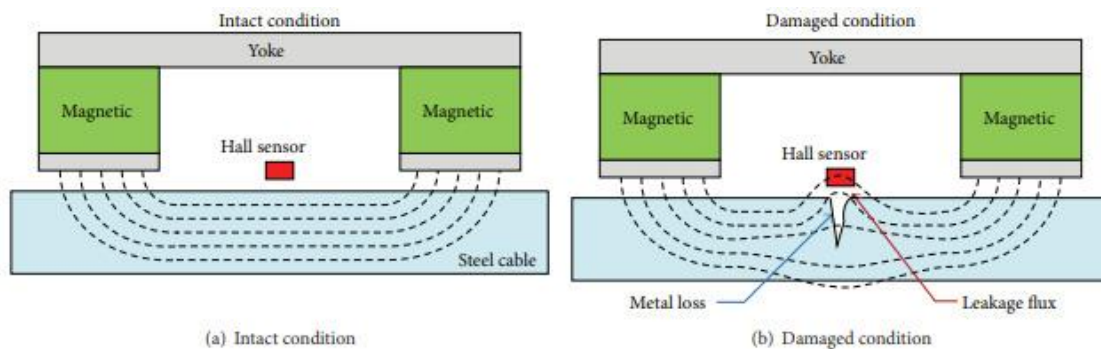


Figure 32: MFL test schematic (Farhangdoust & Mehrabi 2019)

The efficiency of the MFL approach in spotting corrosion in RC structures can be influenced by several variables. Sharif et al. (2020) elaborated that the amount of corrosion, the size and depth of the reinforcement bars are few of these variables. Additionally, Augustyniak and Usarek (2016) suggested that the permeability of the concrete would also have an effect on MFL reading. Furthermore, Zhao et al. (2019) claimed that the quality and accuracy of the MFL detection are also greatly influenced by the sensor's position compared to the specimen under testing. They suggested that it has to be perpendicular to achieve the best results.

2.7.5 Optical Sensing Methods:

1. Fiber Optic Sensors:

Sakiyama, Lehmann and Garrecht (2021) elaborated that due to the total inertial reflection concept, the glass fiber functions as a waveguide to maintain light traveling through the core. The optical and geometrical changes in an optical fiber can also be used to measure various environmental variables. Taheri (2019) clarified that sensitive changes in temperature, strain, and rotation can be related to changes in the amplitude, phase, wavelength, frequency, and polarization of the transmitted light within the fiber cable. Furthermore, Wang et al. (2023) noted that because of the external change being detected, these sensors work by modifying the properties of light (intensity, phase, polarization, wavelength, or transit time) guided via the fiber. Additionally, Hu et al. (2022) articulated that a fiber optic sensor with a coating that reacts to corrosion products, altering its optical characteristics and changing the signal delivered via the fiber, is commonly used for corrosion detection.

The effectiveness of fiber optic sensors in detecting corrosion is dependent on a number of parameters. These include the sensor type, the coating material's sensitivity and selectivity to corrosion products, the coating's stability and durability in the extreme circumstances found in RC structures, and the coupling efficiency between the fiber and the coating (Soman, Wee & Peters 2021; Hu et al. 2022). Moreover, Taheri (2019) commented that there are other crucial elements which include the installation procedure of the sensor, calibration, and data interpretation procedures.

Spatial Distribution-Based Fiber Optic Sensor Categorization

Fiber sensors are categorized in the literature based on their spatial distribution into point sensors, quasi-distributed sensors, and distributed sensors. Figure 33 below shows the main categorization with examples of the most common sensors under each category:

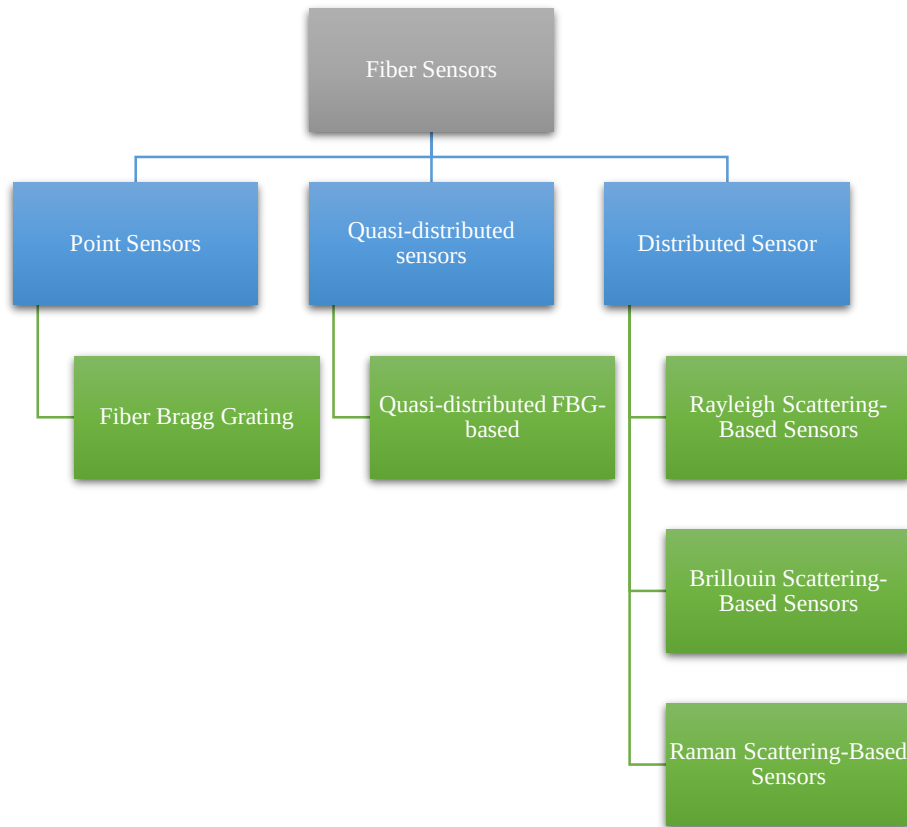


Figure 33: fiber sensors categories

Point Detectors

Alwis, Bremer and Roth (2021) and many others explained and elaborated that point sensors are small, localized devices that measure changes along a single fiber. The Fiber Bragg Grating (FBG) sensor is a prime example of a point sensor. An FBG sensor is a form of intrinsic sensor in which the fiber itself serves as the sensor. It works by reflecting a certain wavelength of light via a periodic fluctuation in the refractive index of the fiber core. Changes in reflected light caused by corrosion allow for effective corrosion monitoring. Furthermore, Tang et al. (2021) articulated that according to the degradation process being monitored, the FBG fiber optic corrosion sensors will be classified into three groups: chemical reaction monitoring, steel bar corrosion monitoring, and concrete expansion monitoring. Figure 34 shows the principle of FGB sensors and a sample of an FBG sensor.

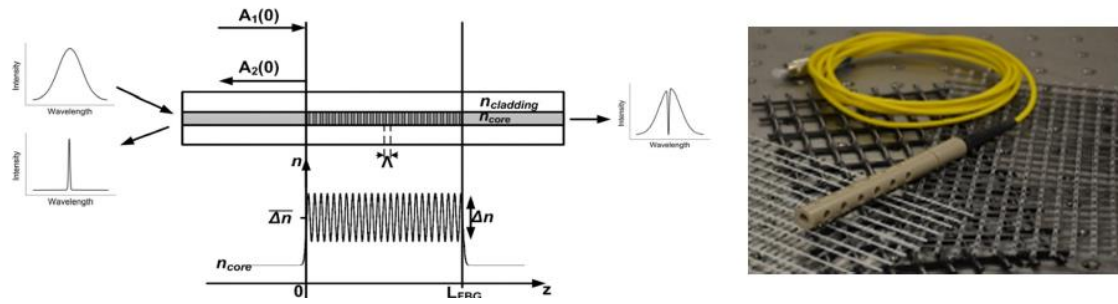


Figure 34: FGB principle and example (Alwis, Bremer & Roth 2021)

Quasi-distributed Fiber Optic Sensor (QDFOS)

Alwis, Bremer and Roth (2021) elaborated that Quasi-distributed FOSs are made up of a network of multiplexed point-based FOSs that enable continuous monitoring of massive structures. Furthermore, because numerous point-based FOSs use the same interrogation unit, quasi-distributed FOSs networks can become more cost-effective. The multiplexing techniques for quasi-distributed FOSs are based on Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM), Frequency Domain Multiplexing (FDM) (Sakiyama, Lehmann & Garrecht 2021), Space Division Multiplexing (Chen et al. 2023), Code Division Multiplexing (CDM), or a combination of these techniques (Alwis, Bremer & Roth 2021). Furthermore, Chen et al. (2023) articulated that due to the ultra-narrow spectral bandwidth, FBG based on the wavelength division multiplex (WDM) principle might create multiplexed arrays. The quasi-distributed FBG sensing network uses signal transmission cables to connect numerous FBGs. It is one of the most widely used wavelength-modulated sensors. Figure 35 below shows the operating principle of the FBG-based quasi-distributed sensors.

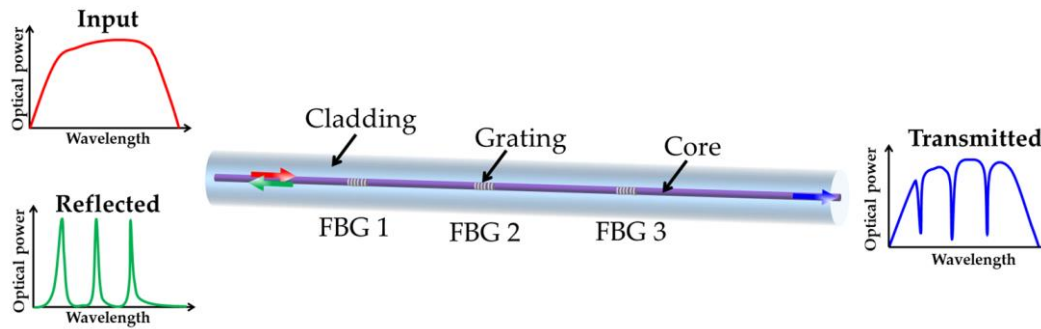


Figure 35: operating principle of quasi-distributed FBG sensor (Chen et al. 2023)

Distributed Fiber Optic Sensor (DFOS)

Sakiyama, Lehmann and Garrecht (2021) elaborated that a DFOS is distinguished by its capacity to function as a sensor along the whole length of a FO cable. The measurement of DFOSs is based on the natural variability of light intensity in the fiber caused by the ordinary manufacturing process. The basic idea is to send a narrow light pulse through the FO wire and evaluate the backscattered radiation. The spotted signal can be used to analyze the local loss distribution or reflections along the fiber, allowing the 'time of flight' to be used to calculate the position of the defect. Additionally, Deng et al. (2023) argued that there is a significant research emphasis for sensing measurements for tens of hundreds of measurement points using a single fiber optic connection. For example, a DFOS can provide a full view of a structure's corrosion status. Furthermore, Alwis, Bremer and Roth (2021) pointed out that DFOS's can be categorized according to the physical effect that its operating principle has (figure 36 below shows an example of a signal's several frequency components caused by different DFOS's). Here are some distributed sensor examples:

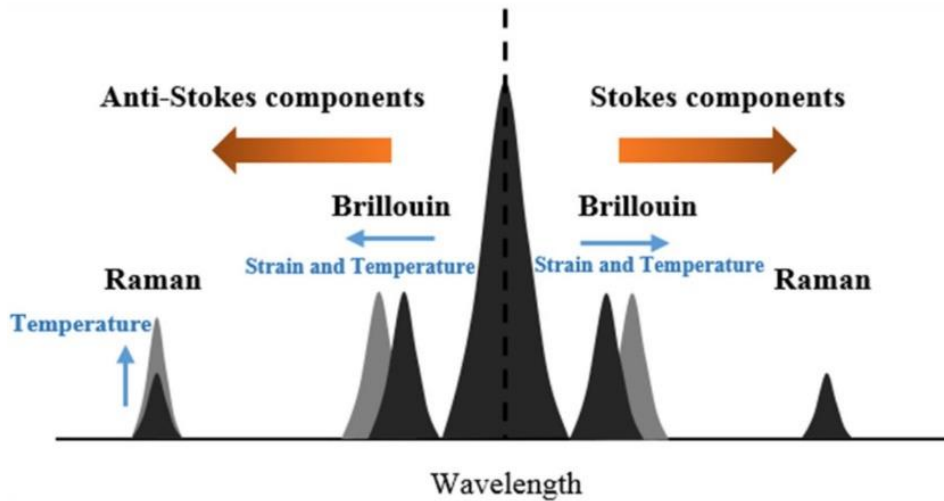


Figure 36: an example of a signal's several frequency components caused by Rayleigh, Brillouin, and Raman scattering(Alwis, Bremer & Roth 2021)

Rayleigh Scattering-Based Sensors

Alwis, Bremer and Roth (2021) highlighted that Rayleigh scattering is the elastic scattering of light by particles considerably smaller than the light wavelength that serves as the foundation for sensing techniques such as Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR).

Sensors for Optical Time Domain Reflectometry (OTDR)

In OTDR based sensor, an optical light pulse from a light source, with a coherence length shorter than the pulse length, is linked into an optical and the Rayleigh scattering backscattered light is recorded using a photodetector. When the received light is time-stamped, the attenuation profile optical fiber link may be examined, allowing the position of splices and connections, as well as optical fiber link breakages, to be determined, as shown in Figure 37 (Ye, Su & Han 2014; Alwis, Bremer & Roth 2021; Tang et al. 2021; Wang, Guo, et al. 2023).

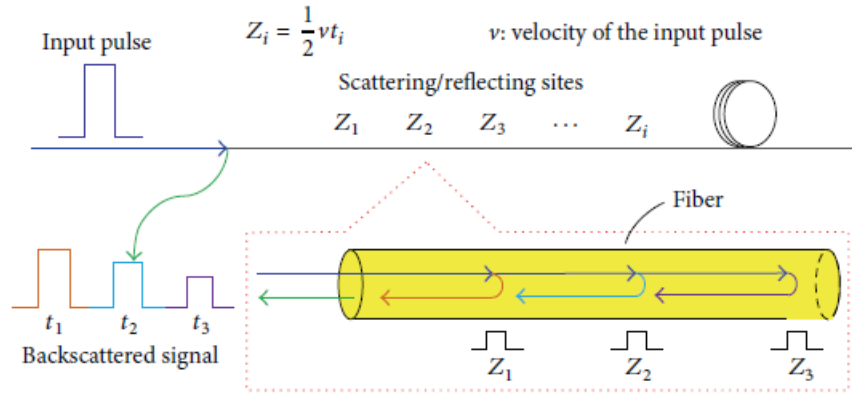


Figure 37: OTDR operating principle (Ye, Su & Han 2014)

Sensors for Optical Frequency Domain Reflectometry (OFDR)

Tang et al. (2021) elaborated that optical frequency domain reflectometry (OFDR) is based on Rayleigh backscattering, and Figure 38 depicts the basic design of a typical OFDR fiber optic sensor. A 3 dB coupler splits a continuous wave (CW) light from a swept-wavelength laser source with a time-linear sweep-changing frequency into two light beams: one goes into the detecting fiber and the other goes into the reference fiber. Because of the existence of impurities and inhomogeneities, the light beam travelling in the fiber will continually create Rayleigh backscattering along its length. At the coupler, the Rayleigh backscattering light is mixed with the reference light beam and detected by a photon detector. External parameters such as strain and temperature alter Rayleigh backscattering in the sensor fiber, causing a shift in the Rayleigh backscattered spectrum. As a result, by measuring the Rayleigh backscattered spectral frequency shift at various sites along the detecting optical fiber, the strain and/or temperature distribution can be observed (Alwis, Bremer & Roth 2021; Sakiyama, Lehmann & Garrecht 2021).

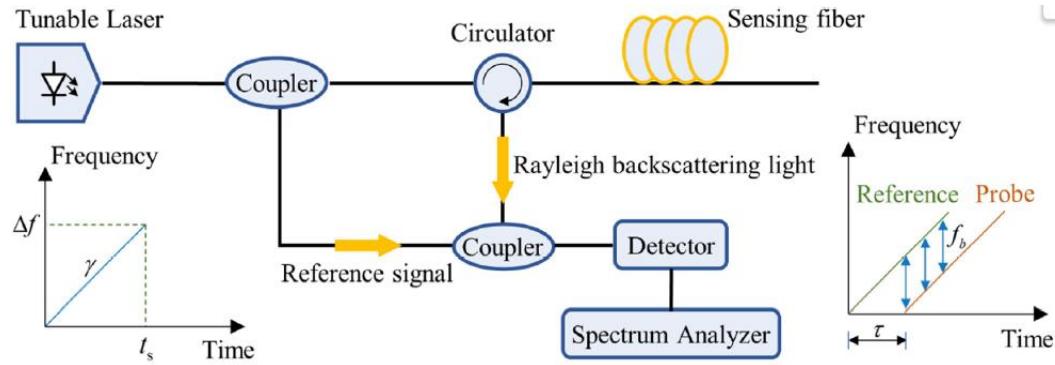


Figure 38: OFDR schematic (Tang et al. 2021)

Brillouin Scattering-Based Sensors

Tang et al. (2021) articulate that Brillouin optical time domain reflectometry (BOTDR) and Brillouin optical time domain analysis (BOTDA) are two commonly utilized Brillouin backscattering-based distributed fiber sensing methods. The two methods are described as below:

Galindez-Jamioy and López-Higuera (2012), Alwis, Bremer and Roth (2021), and Tang et al. (2021) elaborated that BOTDR-based fiber optic sensors are based on spontaneous Brillouin scattering (SpBS), which is an inelastic scattering process caused by the interaction of an incident light wave with an optical fiber's thermally generated acoustic wave field. When an optical pulse is injected into the fiber and propagates forward, it will continually produce spontaneous Brillouin backscattered light along the length, as seen in Figure 39a. As a result, by examining the time period corresponding to each individual position, the spatial distribution of different places of spontaneous Brillouin backscattered light excitement over the length of the fiber can be reconstructed. If the fiber is subjected to external interference, such as strain or temperature change, the spontaneous Brillouin backscattered light will experience a frequency shift, which is known as the Brillouin frequency shift.

Bao and Chen (2011), Galindez-Jamioy and López-Higuera (2012), Alwis, Bremer and Roth (2021) and Tang et al. (2021) clarified that BOTDA is a more sophisticated version of

BOTDR with a stronger detected signal since it employs stimulated Brillouin scattering via two counterpropagating light pulses. Figure 39b depicts the basic design of a typical BOTDA sensor. Two counterpropagating light waves, a pulse light and a continuous wave light, are injected into the two ends of the sensor fiber, respectively, in the BOTDA technology. Stimulated Brillouin scattering happens when the difference between the two light frequencies equals the Brillouin frequency shift.

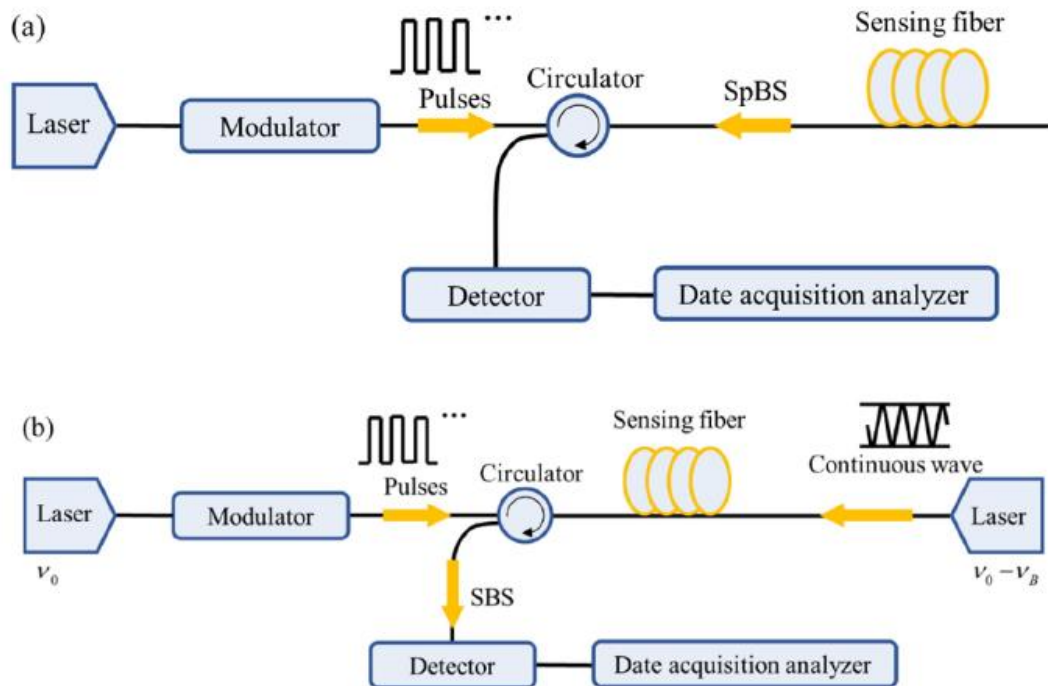


Figure 39: a. schematic of BOTDR b. schematic of BOTDA (Tang et al. 2021)

Raman Scattering-Based Sensors

Alwis, Bremer and Roth (2021) elaborated that when light travels through an optical glass fiber, some of it is backscattered due to molecular oscillations that occur at a wavelength shift relative to the incident light wavelength. The latter result is known as Raman scattering, and it is another nonlinear phenomenon. Nevertheless, Wang et al. (2023) clarified that the interaction of photons travelling in an optical fiber with thermally vibrating molecules causes Raman scattering. If a portion of the light energy is transformed into the energy of molecule

thermal vibrations, light with a longer wavelength is released. This is known as Stokes light, and it is almost temperature independent. On the contrary, converting some of the energy of molecular thermal vibrations into light energy results in the emission of light with a shorter wavelength. This is known as anti-Stokes light, and it is temperature dependant.

Furthermore, Alwis, Bremer and Roth (2021) explained that the intensities of both the Stokes and anti-Stokes bands are temperature dependent, with the anti-Stokes band being more temperature sensitive than the Stokes band. As a result, the temperature at any point along the optical fiber may be calculated using the ratio of the intensities of the anti-Stokes and Stokes bands. As a result, Wang et al. (2023) commented that the temperature profile throughout the optical fiber as a function of location and time can be measured using Raman Optical Time Domain Reflectometry (ROTDR).

2.7.6 Mechanical Methods:

1. Rebound Hammer Test:

The Rebound Hammer Test is carried out on particular grid-defined locations of structural components with the goal of assessing the condition of the concrete cover (Anand et al. 2021). Dhungana, Mishra and Aithal (2022) stressed on the fact that it is crucial to choose a suitable testing location that is smooth, clean, dry, and free of loosely clinging scales that can be removed using a grinding wheel or stone. Rough surfaces can be the consequence of insufficient compaction, grout loss, spalled, or tooled surfaces, among other causes. It is possible to conduct horizontal testing on vertical surfaces or vertical tests on horizontal ones by holding the rebound hammer at a right angle to the concrete surface, figure 40 shows the test schematic.

Anand et al. (2021) elaborated that the Rebound Hammer Test's core tenet is that strength and surface hardness of the concrete are correlated. By applying a certain amount of energy to activate a spring-loaded mass and measuring the subsequent rebound of a rider on a

graduated scale, this relationship is created. According to IS 13311 (Part 2):1992 (BIS, 1992), the relative compressive strength is calculated from the rebound number and compared to the concrete's cube compressive strength. Lower strength and stiffness concrete will have a lower rebound rating because it absorbs more energy. According to Monteiro et al. (2009 in Anand et al. (2021)), field investigations using several cores and rebound hammer testing should be carried out to determine the accuracy of strength forecasts made in accordance with EN 13791. This would increase decision-making confidence in the outcomes of strength tests. The area of dark concrete is more prevalent in concrete mixes with high rebound values, making the mixture appear visually denser and implying poorer permeability and porosity. Those with low rebound values, on the other hand, are lighter in colour, appear to be weaker and more friable, and hence likely have high permeability and porosity (Melchers & Chaves 2020). Dhungana, Mishra and Aithal (2022) commented that, these properties are associated with high aggregate-cement ratios and low cement concentrations (low w/c ratios). In contrast to those with light-coloured concrete near the steel bar, which showed a large quantity of rust, specimens with dark-coloured concrete showed minimal to no rust, indicating little to no corrosion. Dhungana, Mishra and Aithal (2022) summarised the hammer test reading and its interpretation in terms of concrete quality, as shown in table 4:

Table 4: rebound number and its interpretation.

Hammer Rebound Number	Interpretation
>40	Very good
40> and >30	Good
30> and >20	Fair
<20	Poor
0	Delaminated

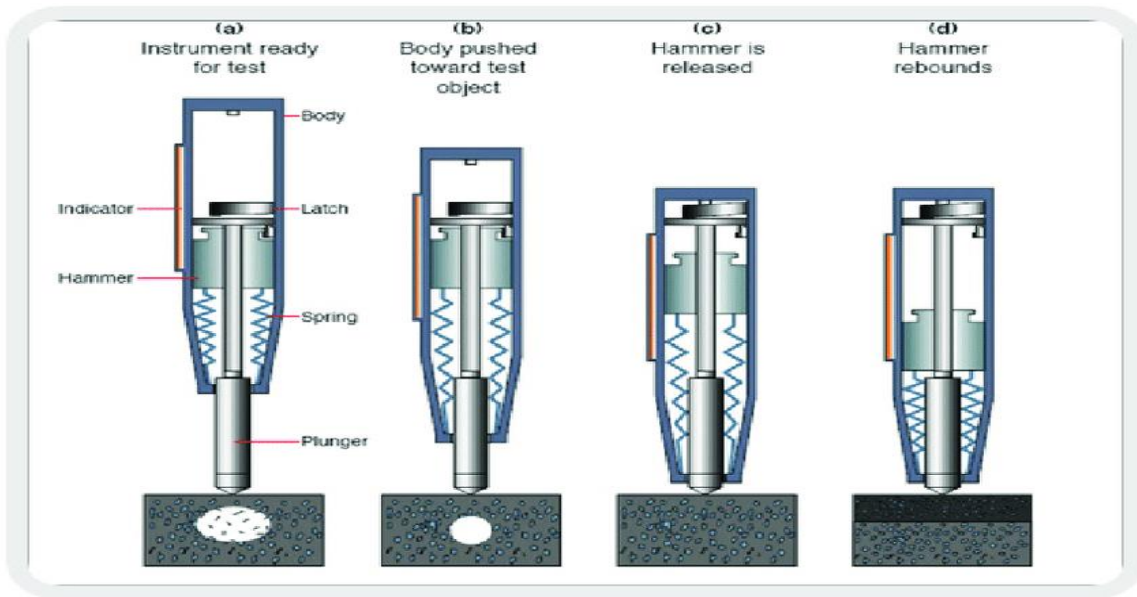


Figure 40: rebound hammer test schematic (Dhungana, Mishra & Aithal 2022)

2. Pull-Out Test:

As clarified in ASTM International (2015), the primary premise of the pull-out concrete test is the link between the strength of the concrete and the force needed to remove a specific piece of reinforcement from the surrounding concrete. To determine the overall resilience and durability of the structure, tests are performed on the strength and binding between the steel rebar and the concrete, which are influenced by the degree of corrosion (Abbas et al. 2022). As discussed by Robuschi et al. (2021) A pull-out test can be used to detect corrosion, which frequently takes the form of a volume increase in the rebar that causes cracking and spalling of the concrete cover. Figure 41 shows a basic setup for a pull-out test.

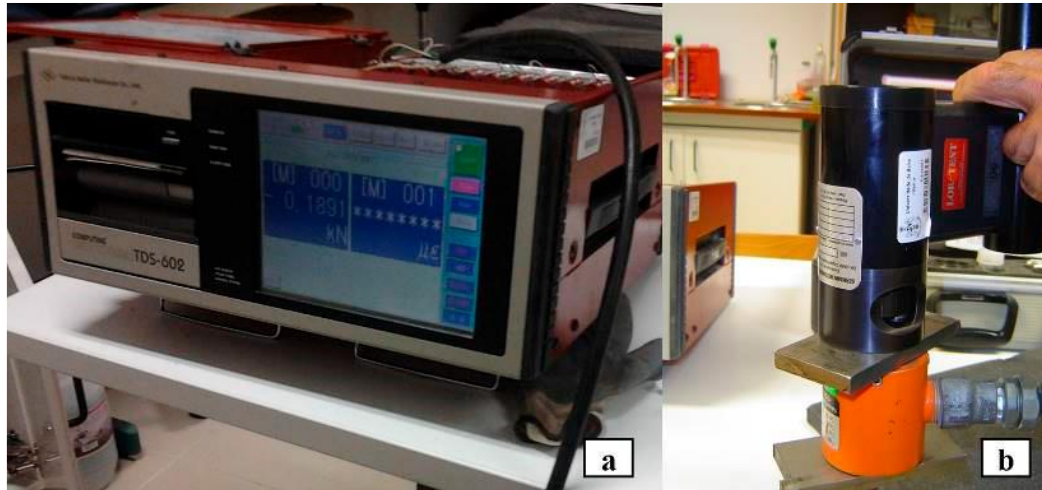


Figure 41: pull out test setup(Nepomuceno & Bernardo 2019)

Preparation, extraction, and analysis are the three general processes of a pull-out test technique(Robuschi et al. 2021). A small reinforced concrete specimen with defined qualities and dimensions is cast during the preparation stage, often with the rebar embedded in the middle(Abbas et al. 2022). This specimen is put through controlled corrosive environments or agents after the correct curing, replicating the field conditions. Using hydraulic jacking, the rebar is extracted from the specimen while meticulously gauging the required force. This force is a crucial gauge of the extent of corrosion since it reveals the strength of the link between the concrete and rebar as detailed in ASTM International (2015). The pulled-out rebar and concrete specimen are lastly examined for corrosion during the analytical step. By considering elements including the rebar's weight loss, changes to its cross-sectional area, and modifications to the chemical composition on its surface, the degree of corrosion may be evaluated(Robuschi et al. 2021).

3. Penetration Resistance Test (PRT):

Designed to gauge the concrete's surface hardness, the Penetration Resistance Test (ASTM C803/C803M) is a non-destructive testing technique. In this test, the resistance provided by the concrete to the penetration of a pin or probe into the concrete surface is measured. This resistance is principally controlled by the concrete's surface hardness, which is in turn influenced by the cement paste's degree of hydration, the mix's composition, and the water-

cement ratio. Additionally, the presence of aggressive substances and the resulting corrosion have an impact. Therefore, the degree of corrosion in the concrete can be inferred from the penetrating resistance (Solanki et al. 2023). Windsor probe system shown in figure 42 is a very common method in literature (Demir, Ulucan & Alyamaç 2023).



Figure 42: penetration tests instruments and test setup(Al Qurishee et al. 2019)

Penetration resistance test has no direct relationship with corrosion in RC structures. However, a reduced penetration resistance result would give an indication for the need to perform further testing to verify the health of the RC structure and the corrosion existence/status.

CHAPTER THREE: METHODOLOGY

García-Peñalvo (2022) elaborated that state-of-the-art reviews are an essential component of academic study, providing contextualizing and validating new research findings within established knowledge areas. It is frequently used in literature to present an overview of existing ideas, highlight patterns, and reveal gaps that require additional inquiry. Their significance extends to new research project applications, where they validate the uniqueness and significance of the proposed work. In the same context, Grant and Booth (2009) distinguished state-of-the-art reviews from other types of literature reviews by addressing more current concerns. It can also offer fresh insights on a subject, pointing out areas that need further examination. These evaluations do not analyze the retrieved sources, but rather convey the current state of knowledge, trends, and limitations of the study field using a combination of narrative and tabular methodologies.

On the other hand, Grant and Booth (2009) argued that state-of-the-art reviews published by subject matter experts tend to provide an accurate assessment of current knowledge and future research objectives. The review may also capture an informal consensus among other experts, depending on the level of communication within the chosen topic. Nonetheless, because of its freshness, a state-of-the-art review may describe a perceived gap in the evidence that is already being addressed, or has already been corrected, but has yet to be published.

Furthermore, discussed that when doing a state-of-the-art literature review, authors must build a three-part argument about the current level of knowledge about a given phenomenon. According to Barry, Merkebu and Varpio (2022), it should include where we are now (present understanding), how we got here (historical overview), and where we might go next (future directions). This method contextualizes the research topic effectively, offering a thorough snapshot of the state of the art.

Conducting a state-of-the-art literature review necessitates a methodical and rigorous approach. While precise procedures may differ based on the subject of study and the research

question, the following steps are the steps (influenced by the work of Barry, Merkebu and Varpio (2022) and shown in figure 42 below) which were followed in this research:

1. Establish the research question: this will serve as a guide for the remainder of the evaluation process. The question should be straightforward, well-defined, and pertinent to your subject of study. For this work, questions were defined after surfing through tens of articles that describe the common RC structures flaws, its rehabilitation process, and its relationship to corrosion. Based on the initial readings, corrosion was selected as a main theme for the dissertation and research questions were established around it.
2. Create a review protocol: a review protocol specifies the processes and procedures to be followed during the review. This usually comprises search tactics, inclusion and exclusion criteria, data extraction and synthesis processes, and preparations for dealing with potential biases. For this work, the strategy was to start with the broad topic of concrete structural deficiencies and move toward more specific topics about corrosion monitoring. Furthermore, the researcher took a decision to include only the most common monitoring technique groups and cover each group from the perspective of different Subject Matter Experts (SME). Capturing the common understanding and highlighting the differences.
3. Identify suitable sources: begin by looking through databases and indexes related to your topic of study. To ensure that you capture as many relevant sources as possible, you should employ a range of search phrases and combinations. Remember to manually review the reference lists of the papers you uncover, as this may lead to other sources. In this work, due to the limited number of available resources, BUID library website as well as google scholar were the sources of literature.
4. Screening and selection of studies: apply your inclusion and exclusion criteria to the search results. This is often done in two stages, with titles and abstracts being screened first, followed by full-text screening of possibly relevant papers. In this study, similar approach we followed while considering the peer-review and the 5-year maximum age as an initial filter for the selected articles to maintain a reasonable level of reliability and validity (Wicherts 2016) with some exceptions on the date of the articles where it was necessary.
5. Data extraction: take significant information from the research you've chosen. Details on the study's design, participants, interventions, outcomes, and results could

all be included. The exact data to be extracted will be determined by your research topic and the objective of your review. In preparation for this study, significant information required to build this study was extracted from its original articles with proper tags for the article and the authors to ensure proper citation.

6. Analyze the retrieved data to detect patterns, themes, and gaps in the literature. This could include qualitative (narrative or theme) synthesis, quantitative synthesis (e.g., meta-analysis), or a combination of the two. In this study, qualitative blend was employed to investigate the collected data, define the outline of every corrosion monitoring technique under study and point out the gaps.
7. Present findings: Summarize the review's findings in a clear and concise manner. This should include a description of the studies included in the review, the primary findings, and an interpretation of the findings in relation to the overall evidence base. The findings of this work were summarized and presented in groups according to its technological category in corrosion monitoring system.
8. Discussion and implications: Discuss the findings in the context of the field, emphasizing the implications for future research, policy, or practice. In this part, researchers' recommendations, notes as well as comments on the future work were captured and discussed.

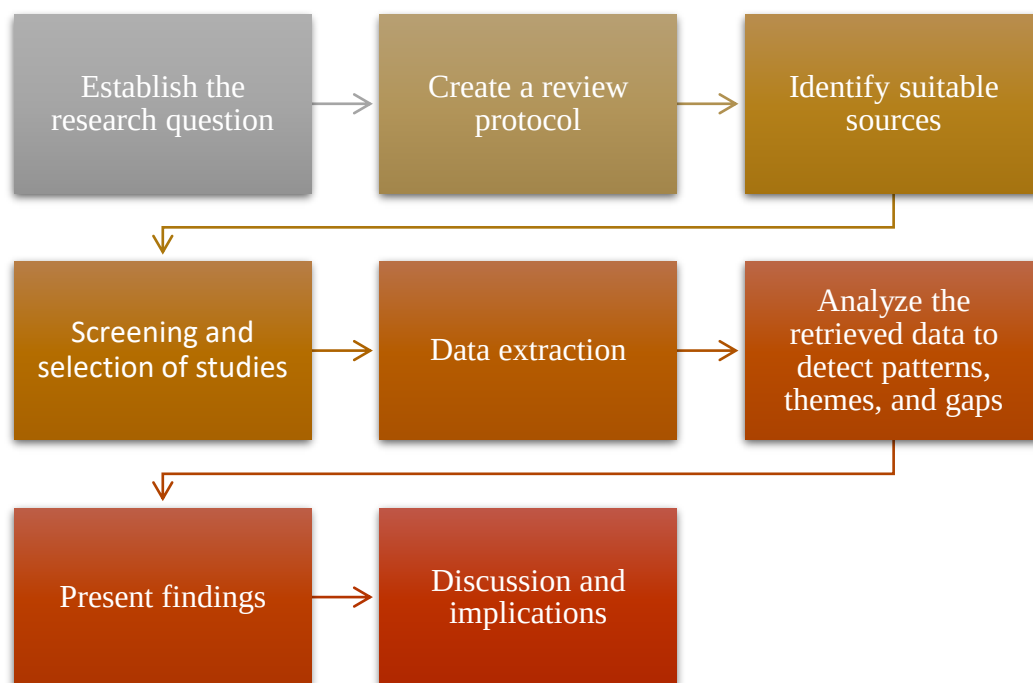


Figure 43: research methodology

CHAPTER FOUR: FINDINGS AND DISCUSSIONS

Corrosion in reinforced concrete (RC) structures has been identified as a primary cause of degradation that can impact RC structures serviceability, durability, and safety. The process is often slow and invisible until considerable damage occurs, resulting in high financial demands for maintenance and repair (Zhang & Li 2020; Van Steen & Verstrynge 2021). For instance, Zhang and Li (2020) articulated that corrosion is extremely damaging in coastal areas where structures are exposed to high amounts of chloride, resulting in a decrease of RC structures performance. As a result, there is an urgent need for reliable corrosion detection and monitoring systems.

On the same context, Manhães et al. (2021), Majhi et al. (2022) and many others argued that the growing economic and environmental costs of RC structures maintenance and rehabilitation intensify the need for effective corrosion monitoring approaches. Regular and trustworthy RC structures inspection can help to reduce the negative economic and environmental consequences associated with structure rehabilitation. Besides, Van Steen and Verstrynge (2021) and Tesic et al. (2022) commented that effective corrosion monitoring and early identification can also contribute to preventative maintenance plans, potentially extending the structure's service life. As a result, developing monitoring approaches and data-driven management strategies to ensure the safe usage of vital concrete RC structures is critical (Verstrynge et al. 2022).

Additionally, Alsharqawi, Zayed and Shami (2020), Álvarez, Hernández Martín and Carraz Hernández (2023) and others elaborated that monitoring approaches are broadly classified as destructive or non-destructive. Destructive tests involve the removal and destruction of concrete samples, providing immediate and accurate results. However, they are not suited for frequent usage due to their intrusive nature, time-consuming processes, and high cost. However, according to Li et al. (2021), Non-destructive tests (NDT) are conducted without causing external damage and are generally based on physical characterization methods such as electromagnetic response and acoustic signals. They are less expensive and harmful than destructive approaches, but their outcomes frequently require expertise to be useful (Alsharqawi, Zayed & Shami 2020).

Moreover, Zaki et al. (2018) highlighted that NDT technologies have great potential for both new and aged structures. They can be a key instrument for quality control of materials or construction in new structures, and they can provide critical feedback for detecting and recognizing degradation in old structures. In addition, Tesic et al. (2022) claimed that the increased sophistication of NDT technologies, notably their capacity to display data, has led to an increase in their popularity and application in corrosion monitoring.

From a different angle, Hu et al. (2022) and Luo et al. (2018) underlined that in the literature monitoring methods are further characterized as direct and indirect. Direct approaches use electrochemical or physical methods to monitor factors such as corrosion potential, corrosion rate, and steel quantity. In contrast, indirect approaches monitor parameters relevant to the corrosion reaction process or corrosion-induced damage. The former comprises characteristics such as chloride concentration, concrete pore solution pH values, concrete carbonation depth, and concrete resistivity, whereas the latter concentrates on corrosion-induced concrete cracking and steel strain redistribution (Kot et al. 2021; Hu et al. 2022).

Non-Destructive Testing (NDT) approaches have attracted the interest of several countries and researchers, with a focus on refining and developing these methods for concrete durability assessment (Robles, Yee & Kee 2022). Additionally, Zheng et al. (2022) articulated that various engineering principles from the fields of materials science, cracks mechanisms, physical characteristics, mechanical engineering, electronics, computer and information technology, machine learning and artificial intelligence were used to build non-destructive testing and evaluation technologies. Robles, Yee and Kee (2022) highlighted that the fundamental advantage of these approaches is their ability to evaluate corrosion-related parameters quickly, safely, and accurately. Visual inspection, electrochemical methods, elastic wave propagation methods, electromagnetic methods, optical sensing methods, and mechanical methods are among the several NDT methods that have been identified (Alhawati, Khan & Ashour 2020; Hassani & Dackermann 2023).

Based on an extensive literature review, it is worth noting that irrespective of the core processes that each of these techniques is employing to perform the functionality of

corrosion monitoring, each has advantages and drawbacks over others. However, combining different techniques based on the site conditions and test purpose and environment would provide the practitioner with the best possible results. In the following section, common combinations mentioned in the literature will be discussed, and a light will be shed on the pros and cons of each technique in the previously mentioned categories.

4.1 Visual Inspection:

For determining the level of corrosion in concrete structures, the traditional approach of visual inspection has been extensively used, with a particular focus on reinforcement corrosion (Zaki et al. 2015). However, Luo et al. (2018) argued that operators use this method most frequently to physically inspect the construction, occasionally with the help of binoculars, magnifiers, micrometers, hammers, and cameras. Despite being widely used, Zaki et al. (2018) and Fornasari, Capozzoli and Rizzo (2023) debated that this method's success mostly depends on the knowledge and experience of the inspector, and it particularly struggles to find corrosion that isn't visible to the naked eye.

Furthermore, de Alcantara et al. (2015) and Luo et al. (2018) highlighted that because of this reliance on observable indicators, considerable hidden corrosion in the structure may already exist by the time damage signals, such as cracks and spalling, become visible. Consequently, visual inspection frequently provides a superficial diagnosis that is restricted to the visible and exposed elements of structures and is heavily reliant on the concurrent structural, environmental, and loading conditions at the time of inspection (Sakiyama, Lehmann & Garrecht 2021). Additionally, Zaki, Murdiansyah and Jusman (2021) claimed that manual visual checks are ineffective, slow, biased, prone to false alarms and interpretations.

These limitations of visual inspections are addressed significantly by the new technology. For example, Luo et al. (2018) discussed that unmanned aerial vehicles (UAVs) have begun to take the place of conventional inspection equipment which provide more safety, efficiency, and affordability in the form of first-stage field inspection capabilities. The input of the first stage will be analyzed using a second stage of image processing powered by AI

capabilities in the advanced models. In addition, Sakiyama, Lehmann and Garrecht (2021) argued that to maintain the health of civil infrastructures and users' safety in addition to UAVs, structural health monitoring (SHM) can be used as a supplement to routine visual inspections. In the same context, Komary et al. (2023) debated that an effective, quick, and practical replacement for manual visual inspections is provided by a new form of visual inspection that is based on automated image capturing and processing. Here, an image of the inspected region is captured by a high-resolution camera and analyzed utilizing image analysis methods. In comparison to conventional visual examination approaches, this method yields more accurate results (Zaki, Murdiansyah & Jusman 2021).

Robotics technology, in addition to UAVs and image processing, has started to extend inspection reach into previously inaccessible or dangerous places (Pfändler et al. 2019), while drones offer new overhead viewpoints for large and high-rise structures and vice versa (Komary et al. 2023). However, Negi et al. (2023) argued that these new innovations are intended to supplement visual inspection rather than to replace it. The combination of human expertise and technical resources results in a more robust and thorough approach to corrosion monitoring, a blend of the old and new that is essential for maintaining and protecting the resilience and safety of reinforced concrete structures.

4.2 Electrochemical corrosion monitoring methods:

Because they can forecast the likelihood and severity of corrosion, electrochemical approaches have been found to be useful for understanding corrosion in concrete structures as discussed by Majhi et al. (2022) and many others. However, Liu et al. (2020) and many others claimed that the steel bar's corrosion quantity cannot be determined using the electrochemical method; it can only be calibrated. Therefore, the demand for a more practical and efficient corrosion detection method is imperative. In similar discussion, Ma et al. (2019) elaborated that conventional electrochemical monitoring techniques have difficulties and restrictions due to the produced rust and conductivity changes that may impact the data. Additionally, as additional interference is required and conventional electrochemical methods can only obtain the average electrochemical data for a specific region over a specific

period of time, they are unable to clearly identify localized corrosion or evaluate cumulative corrosion processes, which will affect the accuracy of the test results.

Furthermore, Van Steen and Verstrynge (2021) articulated that the likelihood, pace, and location of ongoing corrosion processes can be determined from the earliest stages using a variety of electrochemical techniques, such as half-cell potential, the galvanostatic pulse method, and linear polarization resistance. However, they typically depend on the inspector, the condition, and the material and do not allow for ongoing structure monitoring, necessitating specialized monitoring (Shevtsov et al. 2022). Additionally, the findings of various non-destructive techniques, such as half-cell potential and linear polarization resistance tests, rely on the measuring environment and the materials used (Verstrynge et al. 2022).

There have been suggested alternatives for corrosion detecting technologies. Tesic et al. (2022) suggested that the capacity of Ground Penetrating Radar (GPR) to identify the development of the corrosion process, as opposed to other electrochemical methods that only revealed modest changes, has been compared with other electrochemical methods. According to Chang, Tsai and Shiau (2022), GPR has been found to have greater sensitivity to steel bar corrosion than electrochemical corrosion potential detection. By monitoring and analyzing potential and current fluctuations during the nucleation of rebar corrosion, the electrochemical noise (EN) approach has also demonstrated promise for the early evaluation of rebar corrosion (Kawasaki, Fukui & Fukuyama 2022). Additionally, it was claimed by Okenyi and Alawode (2021) that despite its time-consuming nature, which could be mitigated when combined with the galvanostatic pulse method, the electrochemical impedance spectroscopy method has proven to be a very significant technique when it comes to understanding the mechanics and kinetics of reinforcement corrosion. This is because it provides an accurate polarization resistance value from reviewed papers that have applied this technique. However, what made linear polarization unique was its capacity to detect chloride content even at very low levels in concrete.

On the other hand, Pagadala, Mundra and Bansal (2022) debated that the best method for assessing passive state corrosion in a chloride-containing environment has been determined to be EIS, while GPT for active and transient states produces rather excellent findings. Non-destructive methods and LPR would yield equivalent results in a carbonation environment, but HCP provides trustworthy results with adjustment in a chloride environment. On a related topic, half-cell potential mapping is a commonly used first detection tool to provide the corrosion state of steel (passive or active) for more in-depth inspection. It is comparatively straightforward to use. However, because it might be challenging to determine the anodic area with accuracy, it might understate the rate of localized pitting corrosion (Hu et al. 2022).

Moreover, the above represents only a few of the advantages and disadvantages of the electrochemical corrosion monitoring methods. Main system-wise pros and cons for the electrochemical corrosion monitoring that were discussed in the literature review is listed hereunder in table 5:

Table 5: electrochemical methods pros and cons

Half-cell Potential Measurement (Open Circuit Potential Measurements)	
Benefits	Limitation and difficulties
- Amiri, Erdogmus and Richter-Egger (2021) and Chaudhari and Swamy (2022) claimed that HCP can detect corrosion regardless of the depth of concrete cover, rebar size, or detailing, and, in addition to revealing corrosion activity at the most external reinforcing layers, it can also indicate corrosion in greater depth. - It helps defining the most critical zones which needs further assessment (Amiri,	- It indicates the likelihood of corrosion but does not directly assess the corrosion rate as argued by Amiri, Erdogmus and Richter-Egger (2021) and Chaudhari and Swamy(2022). - As indicated by Daniyal and Akhtar (2020), and others it can also be influenced by elements like as moisture content, concrete resistivity, temperature, and the existence of a carbonated layer, which can lead to

Erdogmus & Richter-Egger 2021; Rodrigues et al. 2021). • It helps drawing structure potential map in order to prepare for the suitable protection system, like the cathodic protection system (Cavalcante et al. 2020; Daniyal & Akhtar 2020) . • Cost efficient and easy to use which make it one of the commonly used systems (Song & Saraswathy 2007; Amiri, Erdogmus & Richter-Egger 2021) .	incorrect interpretation of results if not properly examined. • Karthick et al. (2019) argued that the components of this system require period maintenance and it shows less stability in case of long time use.
Electrical resistivity	
Benefits	Limitation and difficulties
• The non-destructive nature of the ER method is its primary advantage. It detects corrosion without causing damage to the structure, making it suited for periodic monitoring of RC structures as argued by Daniyal and Akhtar (2020). • The ER approach can offer a two-dimensional profile of the corrosion condition in the concrete cover, allowing the identification of locations at risk of corrosion. The relation between concrete resistivity and the risk of corrosion is identified in Michael, Kennedy and Oba (2021) and summarized in table below.	• It indicates the likelihood of corrosion but does not directly assess the corrosion rate as argued by Shevtsov et al. (2022). • The sensitivity of the result is subject to multiple factor that are out of practioner's control in the field, like humidity, temperature, and chloride ingress (Daniyal & Akhtar 2020). • The sensitivity of the measurement would have a dependency on the raw materials characteristics, water/cement ratio, micro-structure characteristics of the concrete as well as its age(Robles, Yee & Kee 2022). • Readings is affected by the actual distribution of the probes during the test. The different placements of the

	Concrete resistivity reading ρ (K Ω cm)	Risk of corrosion		probes might produce different results as argued Rodrigues et al. (2021).
	$\rho < 5$	Severe		
	$5 < \rho < 10$	Major		
	$10 < \rho < 20$	Minor to moderate		
	$\rho > 20$	Minor		
Linear Polarization Resistance				
Benefits			Limitation and difficulties	
• The fundamental benefit of the LPR approach is that it is non-destructive, allowing for continuous, in-situ monitoring of corrosion in RC structures. Unlike other indirect approaches, it delivers real-time and direct information regarding the ongoing corrosion rate (Faritov et al. 2016). • As discussed by Komary et al. (2023), polarization techniques such as LPR are thought to be highly accurate and easy to interpret. As a result, numerous researchers have attempted to develop low-cost monitoring solutions using either open-source microcontrollers or developed sensing devices.			• It implies uniform corrosion over the reinforcing steel, which is not necessarily true in real-world constructions (Rodrigues et al. 2021). • The LPR method for measuring corrosion current density has the disadvantage of requiring the partial removal of a concrete cover in order to create an electrical connection to the steel (Nikoo, Sadowski & Nikoo 2017).	
Electrochemical Impedance Spectroscopy				
Benefits			Limitation and difficulties	
• EIS is non-destructive, allowing for in-situ monitoring without jeopardizing the structural integrity of the system under			• The analysis of EIS data can be difficult and time-consuming (Rodrigues et al. 2021).	

investigation (Herrera Hernández et al. 2020). • Pagadala, Mundra and Bansal (2022) highlighted the ability of EIS to precisely detect corrosion in extremely resistive cementitious systems. • Fernandez and Mallco (2018) argued that EIS has a small error margin in the measurement process. • It is utilized as a research instrument to recognize the behavior and mechanism of the concrete/steel interface and to expose information about the corrosion kinetics of steel rebar (Daniyal & Akhtar 2020).	• Concrete heterogeneity can result in noise that would hinder the examination of the results (Shevtsov et al. 2022). • Requires a set of complex equipment which makes it less suitable for field measurements (Shevtsov et al. 2022).
The Galvanostatic Pulse Method (GPM)	
Benefits	Limitation and difficulties
• The non-destructive nature of the galvanostatic pulse technique is its primary advantage. Unlike other procedures that may necessitate the removal of some concrete, this technique only necessitates the application of a current pulse (Okenyi & Alawode 2021). • As argued by Shevtsov et al. (2022) when there is no information about the inspected region, GPM is more consistent and accurate than LPR measurements. • As argued by Shevtsov et al. (2022) when there is no stable reference electrode, GPM is more consistent and	• As articulated by Zaki et al. (2015), one of the significant sources of error when measuring the corrosion rate of steel reinforcement in RC structures affected by the electrical signal from the counter electrode and the non-uniform current distribution of the steel reinforcement is uncertainty about the polarized area of the steel reinforcement. • As commented by Shevtsov et al. (2022), there is a need for corrosion engineer on site while using some of the commercially available GPM sensors. • Measurements of real structural parts taken with the GPM at different

accurate than HCP, LPR, and EIS measurements (Zaki et al. 2015).	temperatures (seasons) can result in an incorrect estimation of the probability of reinforcement corrosion in the studied area, as well as an incorrect assessment of its corrosion activity over time. As a result, it is best to specify the proper temperature adjustment factors for measurements taken with the GPM (Raczkiewicz & Wójcicki 2020).
Electrochemical Noise Measurement (ENM)	
Benefits	Limitation and difficulties
• The non-destructive nature of the electrochemical noise technique is its primary advantage (Zaki et al. 2015). • ENM can identify the onset of corrosion before it causes significant damage to the structure (Kawasaki, Fukui & Fukuyama 2022). • Kawasaki, Fukui and Fukuyama (2022) argued that ENM could detect slight pitting corrosion due to its capability to detect its current noise fluctuation. • de Alcantara et al. (2015) articulated that the non-destructive nature of the electrochemical noise technique is its primary advantage, in addition to its low cost.	• The potential map simply gives a hint as to the likelihood of visible corrosion. Without the creation of further mapping and computational models of concrete resistivity, ENM cannot be used to offer such data or directly create local corrosion rates as argued by Mills, Lambert and Yang (2021). • Mills, Lambert and Yang (2021) argued that ENM might not be suitable for site investigation due to the uncontrolled environment conditions. • Cavalcante et al. (2020) argued that one of the limitations of ENM, is the failure to perform mathematical analysis because of the complication caused by the types of noise generated due to RC corrosive process.

4.3 Elastic Wave Corrosion Monitoring Methods:

In this work, Ultrasonic, Acoustic Emission, Ultrasonic Pulse Velocity and Impact Echo were explored as common examples of Elastic Waves. The Acoustic Emission (AE) method, a contact detection method renowned for its capacity to identify elastic-wave generation, is one such approach (Kawasaki, Fukui & Fukuyama 2022). Li, Zhou and Ou (2021) claimed that the foundation of AE monitoring is the idea that damage, such as cracking, can release strain energy from a stressed structure, which can then be converted into an AE signal by sensors such as piezoelectric transducers. This method, however, has certain drawbacks: it is only appropriate for structures with minor damage, and if the interior damage does not change or extend, no AE signal is produced. Furthermore, Shevtsov et al. (2022) pointed out that the AE approach may be noise-sensitive, which is problematic in actual engineering constructions. Transient elastic sound waves are produced as a result of material deformation in the Acoustic Emission (AE) monitoring procedure. These waves are converted into electrical signals by the AE sensors, which are positioned at the material's surface (Kot et al. 2021). While AE is useful for locating and detecting damage in concrete structures in real time, it also has problems with signal attenuation and dispersion in heterogeneous materials like concrete. Due to concrete's significant attenuation qualities, lower frequency sensors are typically better suited for it (Kot et al. 2021).

According to Wu et al. (2021) and May, Alam and Nayan (2022), the ultrasonic approach creates mechanical waves or vibrations in the specimens and uses the ultrasonic waves' reflection at the borders to characterize the material properties. It has been widely employed for thickness measuring and corrosion monitoring, but it also has drawbacks similar to other techniques. The approach has trouble differentiating between reflections from surface/near-surface corrosion and reflections from various material surfaces, and it calls for coupling mediums like water or gel, which may not be appropriate in all circumstances.

Combining the elastic wave techniques allows for efficient early rebar corrosion monitoring. The performance of the elastic wave methods is improved by this combination because it can take into account both the physical and electrochemical mechanisms related to rebar corrosion (Kawasaki, Fukui & Fukuyama 2022). In contrast, laboratory tests using the AE

and HCP methodologies in conjunction revealed good agreement (Shevtsov et al. 2022). Another strategy is presented by Pant and Shrestha (2022) and is based on resistivity data. Their research revealed that concrete corrodes quickly, indicating a rapid loss of strength and a reduction in static modulus of elasticity.

Moreover, the above represents only a few of the advantages and disadvantages of the elastic wave monitoring methods. Main system-wise pros and cons for the elastic wave corrosion monitoring that were discussed in the literature review is listed hereunder in table 6:

Table 6: elastic wave pros and cons

Ultrasonic Testing	
Benefits	Limitation and difficulties
• The primary benefit of UT is that it is non-destructive, in addition to its capability to provide real time results as argued by Liu, Qin and Huang (2018) • UT may identify a variety of faults, including corrosion, delamination, and separate cracks. Also, it can be used to detect corrosion on epoxy-coated bars as argued by Amiri, Erdogmus and Richter-Egger (2021). • Miró et al. (2021) argued that UT provides the ability to identify flaws, crack and damages that cannot be identified by the visual or microscopic inspection. • UT is also adaptable due to its features to capability to cover long and board areas as highlighted by (Liu et al. 2016), UT can be employed on a variety of types of structures, from small buildings	• If the orientation of the discontinuity is not parallel to the direction of sound wave propagation, the approach may fail to discover some faults and requires competent operators for proper interpretation of data as argued by Shevtsov et al. (2022). • UT can be more costly and time-consuming than some other non-destructive testing techniques, in addition to the need for trained staff to test and analyse the results as indicated by Amiri, Erdogmus and Richter-Egger (2021).

to big infrastructures like bridges and dams, and in a variety of environmental circumstances (Marcantonio et al. 2019).	
Acoustic Emission	
Benefits	Limitation and difficulties
Md Nor et al. (2023) argued that AE can provide vast range of information about the RC structure behaviour, early warning signal from various flaws and a monitoring tool to track the progress of these flaws (Verstrynge et al. 2022).	- Md Nor et al. (2023) argued that the accuracy of the AE results is dependent on multiple factors such as: the configuration of the sensor, the precision of arrival time picking, the velocity model, and the wave propagation path as well as sensor sensitivity (Verstrynge et al. 2022). - Verstrynge et al. (2022) claimed that the requirement for adequate data filtering to separate relevant information from noise and the enormous datasets that emerge from the fast collection speed needed to capture the entire waveforms are challenges in AE monitoring. - Verstrynge et al. (2022) highlighted that research for on-site AE monitoring is still in progress. However, AE-based corrosion monitoring has primarily been used in lab tests. - Van Steen and Verstrynge (2021) argued that the investment cost required to operate AE system with an acceptable accuracy level shall not be ignored that feasibility shall always be considered as make or break factor.

Ultrasonic Pulse Velocity	
Benefits	Limitation and difficulties
• It is a non-destructive testing technique, allowing for the evaluation of the structure's integrity without resulting in additional damage (Nanayakkara, Najm & Sabri 2022). • It is a time-effective tool for large-scale inspections since it can quickly evaluate enormous volumes of material. • It is applicable to old as well as new structure (Ndagi et al. 2019). • A reliable indicator of the severity of corrosion and cracks in concrete is the UPV readings (Concha & Oreta 2019).	• Ultrasonic pulse velocity has demonstrated its ability to provide important, non-destructive insights into the consistency and quality of concrete. However, this procedure is susceptible to blunders and failures that could produce misleading results (Ndagi et al. 2019). • Performing this test efficiently, requires the presence of qualified engineer. • Minor flaws caused by steel corrosion in concrete, such as increased porosity and/or micro-, ill-defined, and closed fissures in concrete, are unlikely to have an impact on UPV (Mukhti et al. 2023). • The process of surface preparation and testing on-site must be carried out with great accuracy; otherwise, the results will be more ambiguous (Bolborea et al. 2021). • Nanayakkara, Najm and Sabri (2022) argued that although UPV is independent from the geometry of the test sample, the results of UPV are affected by several variables, including temperature, moisture content, path length, specimen form and size, steel fibre, and reinforcing bars.

Impact Echo	
Benefits	Limitation and difficulties
- Engineers can find weaknesses without endangering the building thanks to Impact Echo's non-destructive nature(Yang et al. 2021). - Zhang, Yan and Cui (2016) argued that IE is suitable for single side detection, easy to use, having relatively larger detection depth; and less influenced by differences of concrete materials and structures. - Yang et al. (2021) claimed that IE can identify both surface and subsurface flaws and provide thorough, precise information about the state of the RC structure. - It is efficient and cost-effective because it can inspect a big area in a short period of time (Scherr & Grosse 2021).	- To effectively understand the signals, you need to have professional knowledge(SANO et al. 2022). - False-positive or false-negative results can be brought on by background noise and signal dispersion (Zhang, Yan & Cui 2016). - The calculation used to find out plate thickness is frequently underestimated due to improper Poisson's ratio assumptions(Scherr & Grosse 2021).

4.4 Electromagnetic Corrosion Monitoring Methods:

According to Li et al. (2020), one important form of electromagnetic sensor monitors corrosion sources based on electromagnetic responses, while the acoustic emission equipment is used to find corrosion-caused fissures. The examination of the complete corrosion process is made possible by the combined application of these two separate monitoring devices. Furthermore, Chang, Tsai and Shiau (2022) claimed that another widely used electromagnetic technique with high sensitivity for determining the degree of corrosion in its early phases is ground penetrating radar (GPR). The process examines variations in the electromagnetic wave's reflected voltage as it responds to corrosion in the steel bar. GPR has benefits over electrochemical potential detection for detecting corrosion, including as less

damaging effects on concrete surfaces and quicker, more accurate assessments of the degree of corrosion. The dense metal layer inside the measured structure, however, may interfere with electromagnetic waves, complicating analysis and lowering test accuracy as discussed by Zheng et al. (2022).

Additionally, Pospisil et al. (2021) reported that it has been demonstrated that using GPR in conjunction with other techniques improves measurement outcomes. For instance, it can improve data accuracy when combined with electromagnetic induction, electrical resistivity, and ultrasonic techniques. On the other hand, de Alcantara et al. (2015) elaborated that in the magnetic flux leakage (MFL) approach, low-frequency electromagnetic fields are used, as are high-frequency electromagnetic fields in ground-penetrating radar (GPR). Further details were added by Robles, Yee and Kee (2022) discussing GPR as a qualitative study technique for corrosion damage, highlighting in particular how corrosion materials and chloride content effect electromagnetic wave attenuation. Infrared thermography, on the other hand, is employed for subsurface inspection by spotting irregular temperature distributions in concrete brought on by rebar corrosion and internal fissures. Hu et al. (2022) added to the same content where he argued that because different materials have varied magnetic characteristics, EM sensors can detect corrosion in reinforced concrete.

In contrast, these techniques have several drawbacks. For instance, according to Hu et al. (2022), the EM sensors' sensitivity for rebar inserted deeper in the cover needs to be increased. Additionally, the orientation of the corrosion thickness with regard to the magnetic flux affects the effectiveness of the EM method's detection. In addition, Hassani and Dackermann (2023) pointed out some of its drawbacks. These include being restricted to electrically conducting materials and being vulnerable to variations in magnetic permeability.

Kot et al. (2021) articulated that to track corrosion, several EM monitoring techniques have been developed. For instance, the ground penetrating radar (GPR) technology is widely employed because of its noninvasiveness, affordability, and quick monitoring. Chang, Tsai and Shiau (2022) claimed that the detection of electrochemical corrosion potential is less

sensitive to corrosion of the steel bar than changes in the reflected voltage of the electromagnetic wave that is propagated from the GPR. Additionally, GPR can identify the severity of steel bar corrosion in its earliest stages. However, Zheng et al. (2022) highlighted that a drawback of GPR is that the dense metal layer inside the measured structure may cause interference, which can make analysis more complex and test accuracy lower.

In a different study, Pospisil et al. (2021) suggested that the combined use of GPR and additional methods such as electrical resistivity, electromagnetic induction, or ultrasonic techniques can be used to enhance the measurement outcomes. In similar context, de Alcantara et al. (2015) recommended combining electromagnetic heat induction with infrared thermography. Despite these developments, EM corrosion monitoring still faces significant difficulties. With observed sensitivity concerns for rebar immersed in deeper cover, the effectiveness of the EM method's detection depends on the orientation of corrosion thickness with respect to the magnetic flux (Hu et al. 2022). Furthermore, Shevtsov et al. (2022) added that the use of portable electromagnets to monitor large constructions and the impact of the electromagnetic field on the condition of the reinforcement in concrete present additional challenges. Additionally, electromagnetic, and magnetic testing techniques are primarily restricted to electrically conductive materials and are inappropriate for complex geometries or wide regions due to fluctuations in magnetic permeability (Hassani & Dackermann 2023).

Moreover, the above represents only a few of the advantages and disadvantages of electromagnetic monitoring methods. Main system-wise pros and cons for the electromagnetic corrosion monitoring that were discussed in the literature review is listed hereunder in table 7:

Table 7: electromagnetic methods pros and cons

Infrared Thermography	
Benefits	Limitation and difficulties
• As argued by Wu et al. (2021), thermography has the benefits of being real-time, non-contact, safe and able to quickly inspect a broad area. • Kot et al. (2021) argued that this approach has been shown useful for making quick assessments of large buildings, specifically high-rise buildings. The development of high-end IR cameras could improve the technique's dependability, precision, and cost-effectiveness in the future.	• Wu et al. (2021) claimed that the high cost of high-quality thermal cameras was a disadvantage of the IR approach, but recent advancements have made them substantially less expensive. • Zaki et al. (2015) argued that IRT method does not provide sufficient quantitative information about the corrosion in terms of size and depth. • Zaki, Murdiansyah and Jusman (2021) articulated that the fracture calculation and other damage to concrete structures will be influenced by external temperature and other environmental factors, resulting in a confused and imprecise appearance in thermal images.
Microwave Thermography	
Benefits	Limitation and difficulties
• Li et al. (2023) argued that MWT is advantageous due to its low energy consumption, high penetration, lack of touch, and minimal equipment volume and weight. Similarly, May, Alam and Nayan (2022) suggested that MWT has a high energy efficiency and is easily accessible to the coated materials.	• Expertise is necessary for the interpretation of thermal images, which can be made more difficult by things like uneven heating or the presence of other materials that might change the thermal patterns as discussed by Farhangdoust and Mehrabi (2019). • Wu et al. (2021) argued that only surface corrosion can be detected

• Li et al. (2019) claimed that microwave NDT has been proven to be beneficial in terms of high efficiency and accuracy in the inspection of conductors with surface defects. • Brinker et al. (2020) argued that MWT is particularly sensitive to metal surface characteristics and can detect tight surface-breaking cracks, pitting, and surface roughness.	because microwaves cannot effectively pass through conductive materials; it is challenging to find underlying corrosion. • Wu et al. (2021) argued that MWT is expensive techniques which can limit its utilization.
Ground Penetration Radar	
Benefits	Limitation and difficulties
• Manhães et al. (2021) argued that due to its great resolution, efficiency, and popularity, GPR is one of the most widely used non-destructive testing techniques for infrastructure imaging where photos in real time are accessible. Concrete deterioration might be mapped using GPR scans, which could also be utilized as a decision-making tool for routine and emergency maintenance (Alsharqawi, Zayed & Shami 2020). • Zaki et al. (2018) argued that GPR technology can be widely used in structural engineering where it may be used for locating reinforcing bars, locating cracks, locating, and evaluating voids, locating honeycombed or cracking, detecting corrosion, estimating bar size, determining	• Zaki et al. (2018) articulated that GPR does, however, have some restrictions. The composition, temperature, and moisture content of the concrete, and pulse frequency might affect its efficacy, and it can be difficult to interpret the results without specialized understanding. • Alsharqawi, Zayed and Shami (2020) argued that GPR results' interpretation is not simple and requires trained staff. • (Tescic et al. 2022) claimed that ground-penetrating radar might exaggerate corroded areas when deterioration is mild.

concrete mix proportions, and determining environmental conditions. • Zaki et al. (2018) articulated that using GRP, rebar corrosion can be discovered and determined at an early stage, even before visible damage or other corrosion symptoms have occurred. • Álvarez, Hernández Martín and Carraz Hernández (2023) highlighted that one of the main benefits of GPR is its capability to swiftly and precisely obtain two-dimensional or three-dimensional photographs of the structure, in addition to its capability to cover large areas in a relatively short time(Fornasari, Capozzoli & Rizzo 2023).	
Eddy Current	
Benefits	Limitation and difficulties
• Non-destructive: Because eddy current testing is non-invasive, the structure is not destroyed or disrupted during testing(Daura 2022). • ECT sensors can be simply constructed and operated by employees with only a minimal level of professional training, without the requirement for additional expertise in, say, electrochemistry (de Alcantara et al. 2015). • Real-time results: It can provide instant feedback on the condition of the material being tested, with an economic	• Ha, Lee and and Lee (2021) elaborated that the skin effect restricts the measurable depth even if the approach using a single wavelength since wave correctly monitors corrosion. Utilizing different frequency waves as input signals to assess the structural durability is acceptable since corrosion affects steel frames both internally and outside. However, creating input signals and measuring output signals are necessary for the process of generating numerous frequencies, making it far more expensive and complex than a single

cost, and sustainable impact on environment (AbdAlla et al. 2019).	frequency system and unsuitable for reducing cost or power usage. • The stability and precision of the excitation signal and the energy-efficient response signal pose challenges to the accuracy and stability of the probe (Daura 2022). • Skilled interpretation is required: The data collected is frequently complex, necessitating the use of trained operators to accurately interpret it (de Alcantara et al. 2015).
Magnetic Flux Leakage	
Benefits	Limitation and difficulties
• It is non-destructive where RC structures can be evaluated in-situ without having their integrity compromised (Wu et al. 2021). • Li et al. (2023) argued that MFL offers quick, in-the-moment corrosion detection and visualization, enabling prompt maintenance. • Md Nor et al. (2023) articulated that one of the advantages of MFL is that it provides a reliable assessment of the severity of the tendon strand deficiency.	• Farhangdoust and Mehrabi (2019) articulated that the limited magnetic field penetration makes it difficult to detect corrosion in its earliest stages or at deeper layers of reinforcement. Thus, it is more feasible for near surface detection. • Li et al. (2023) argued that a high degree of knowledge and comprehension of the technique and structure being evaluated are needed for the interpretation of MFL results (Farhangdoust & Mehrabi 2019). • Li et al. (2023) argued that MFL method does not provide sufficient quantitative information about the corrosion.

4.5 Fiber Optic Sensing Corrosion Monitoring Methods:

Okenyi and Alawode (2021) argued that with multiple benefits like chemical resistance, resistance to electromagnetic interference, and lower production costs, fiber optic corrosion sensing technology (FOCS) is becoming a dominating method in monitoring corrosion across a variety of applications. However, Luo et al. (2018) claimed that it is acknowledged that advancements in precision, usability, robustness, and the creation of new sensors can further optimize the application of FOCS.

Furthermore, Tang et al. (2021) discussed that the qualities of the coating layer and the distance of the fiber from corroding sites are the main determinants of the sensitivity and monitoring range of FBG sensors. These sensors monitor corrosion-associated chemical processes inside the coating layer or close to the rebar. However, BOTDR/BOTDA/OFDR distributed sensors indirectly monitor the corrosion of the reinforcement steel by detecting stresses brought on by the volume expansion of the steel rebars or corrosion-induced expansion/cracking of the concrete. On the other hand, Soman, Wee and Peters (2021) argued that compared to BOTDR/BOTDA/OFDR sensors, FBG sensors may be less sensitive in some situations due to a reduced contact area between the fiber and the structure. However, installation techniques, installation material characteristics, and optical instrument demodulation capacity all have a significant impact on the performance of BOTDR/BOTDA/OFDR sensors (Tang et al. 2021).

Additionally, Tang et al. (2021) suggested that the information acquired by FOCS includes, among other things, information on the breadth of concrete cracks, passive film thickness, corrosion initiation time, chloride penetration, mass loss of steel rebar, and passive film thickness. Although these sensors are frequently designed for a particular stage of the corrosion process, the creation of an effective network of fiber optic corrosion sensors could greatly increase their utility and enable more accurate safety assessments or service life predictions. However, Wang et al. (2023) highlighted that the capacity of FOCS to be combined with other technologies to provide a more thorough understanding of a structure's health status makes it special. For instance, numerous experimental research has investigated the pairing of visual sensing technology, which enables non-contact measurement, with fiber

optic sensing technology, which allows contact measurement. This combination may make it possible to integrate interior stresses measured by fiber optic sensing techniques with external strains recorded by vision sensing techniques, providing a structure with more detailed health information.

Moreover, the above represents only a few of the advantages and disadvantages of Fiber sensing methods. Main system-wise pros and cons for the fiber sensing corrosion monitoring that were discussed in the literature review is listed hereunder in table 8:

Table 8: fiber optic sensing methods pros and cons

Fiber Optic Sensing	
Benefits	Limitation and difficulties
• Tang et al. (2021) highlighted that being light-weight, compact, small size, can be multiplexed into a network, corrosion resistance, withstand harsh environment and immune to electromagnetic interference are key advantage for fiber-based sensors (Taheri 2019; Alwis, Bremer & Roth 2021; Soman, Wee & Peters 2021; Chen et al. 2023). • Tang et al. (2021) articulated that the advantage of FBG fiber optic corrosion sensors is that they just require a single-ended connection to the spectrometer. • Alwis, Bremer and Roth (2021) argued that by mapping the measured Brillouin frequency and its time of arrival, BOTDR can measure both temperature and stain characteristics.	• Taheri (2019) argued that the relatively high cost of the sensors and accompanying equipment, potential complications in the installation process in existing structures, and need for advanced data interpretation techniques is among these can be considered as a disadvantage for fiber optic based sensors (Wang et al. 2023). • Bremer et al. (2016) articulated that developing durable, corrosion-sensitive coatings with stable optical characteristics during the lifetime of an RC structure is a significant issue. • Tang et al. (2021) argued that point sensors have a limitation when it comes to large-scale structures application. • Tang et al. (2021) emphasized that the FBG fiber in this corrosion monitoring

• Tang et al. (2021) argued that because it has a higher monitoring range and spatial resolution than other fiber optic sensors, the OFDR fiber optic sensor is a strong contender for monitoring reinforcing steel corrosion.	assembly simply functions as a heat source temperature sensor, and the relationship between the temporal response of the thermal probe and the corrosion-induced mass loss of steel rebar is not well understood. • Deng et al. (2023) argued that low spatial resolution is a common disadvantage for Rayleigh scattering based OTDR sensors and Raman scattering based sensors, while weak measuring range is a common disadvantage for Rayleigh scattering based OFDR sensors and being complex system that requires long time is the common disadvantage of Brillouin scattering based sensors. • Tang et al. (2021) claimed that the BOTDR fiber optic sensor could not only measure strain but also locate crack spots. It is, however, suited for uniform corrosion monitoring, and the monitoring accuracy is influenced by the thickness and qualities of the concrete cover.
--	--

4.6 Mechanical Corrosion Monitoring Methods:

Despite the fact that mechanical methods like rebound hammer test, pull-out test and penetration resistance test has no direct relation to corrosion status evaluation, its test results would provide an indication for the overall health of the RC structure and indirectly to the possibility of corrosion existence.

A non-destructive testing (NDT) technique used to determine the compressive strength of concrete is the hammer test, commonly referred to as the rebound hammer test. The concrete surface is struck by a spring-loaded mass that is released from the hammer, and the rebound distance is measured to determine the strength of the concrete and the hardness of the concrete's surface (Bolborea et al. 2021). However, Ndagi et al. (2019) argued that despite being frequently used, the hammer test's accuracy drops off quickly as concrete strength increases, hence it may not be able to offer accurate estimates of concrete strength when used alone. On the other hand, pull-out tests are used to assess the strength of the bond between the concrete and the embedded reinforcement. These tests shed light on how corrosion negatively affects bond strength. Verstrynge et al. (2022) description of the pull-out test concentrates on the decrease in bond strength brought on by corrosion and provides a clear evaluation of this corrosion-induced damage.

Ultrasonic pulse velocity (UPV) tests and other penetration tests gauge how quickly an ultrasonic pulse can pass through concrete. The concrete's integrity and quality can be inferred from the pulse's rate of beat. Ndagi et al. (2019) pointed out that UPV is a weak method for determining the strength of concrete unless it is used in conjunction with other strength tests, such as the rebound hammer. Additionally, comparisons between these several mechanical corrosion monitoring techniques reveal that every test has certain benefits and restrictions. For instance, the hammer test is simple to do and takes little time, but it only provides a quick evaluation of the concrete's strength and may not be as accurate for stronger concrete (Ndagi et al. 2019). The bond strength between the concrete and the reinforcement, which is directly impacted by corrosion, can be learned via the pull-out test. However, this test might be more intrusive and harmful than the other approaches. The UPV test can evaluate the consistency and quality of the concrete, however it is insufficient to evaluate the strength of the concrete (Ndagi et al. 2019).

Different combinations of the aforementioned tests have been suggested in order to increase the effectiveness and dependability of mechanical corrosion monitoring methods. The SonReb approach, which combines the UPV and rebound hammer tests, has been proven to be successful in overcoming the shortcomings of the separate tests. More accurate estimates are produced by combining the rebound hammer test with UPV measurements to create a

conversion model between test results and concrete strength (Breysse et al. 2019). Similarly, Pant and Shrestha (2022) discovered that a decline in strength and elasticity was indicated by the link between pulse velocity and the outcomes of the rebound hammer test. Resistivity information can be used to estimate the concrete's rate of corrosion and provide additional support for this combination.

Moreover, the above represents only a few of the advantages and disadvantages of mechanical methods. Main system-wise pros and cons for the mechanical corrosion monitoring that were discussed in the literature review is listed hereunder in table 9:

Table 9: mechanical methods pros and cons

Rebound Hammer Test	
Benefits	Limitation and difficulties
• Non-Destructive: The Rebound Hammer Test's main benefit is that it is non-destructive, making it especially useful for assessing completed constructions without causing any damage (Pant & Shrestha 2022). • Fast and Simple: The ability to do the test fast is a big benefit for determining the strength of large constructions (Pant & Shrestha 2022). • Economical: It is comparatively affordable compared to other non-destructive tests, making it a cost-effective option for initial structural evaluations (Pant & Shrestha 2022).	• Surface and Testing Condition Dependencies: Surface characteristics, such as roughness, moisture content, and carbonation, can have a substantial impact on the test findings. The test's orientation—vertical or horizontal—can also have an impact on the outcomes (Dhungana, Mishra & Aithal 2022; Diaferio & Varona 2022). • It does not provide a direct measurement of the concrete's compressive strength, which can only be determined through more invasive methods like core drilling. It simply gives an estimate of the concrete's surface hardness(Dhungana, Mishra & Aithal 2022).

	Limited Depth of Assessment: The test can only evaluate the concrete's quality close to the surface, leaving room for problems that may go undiscovered further inside the structure(Diaferio & Varona 2022).
Pull-out Test	
Benefits	Limitation and difficulties
- Al-Sabah, Alam Sourav and McNally (2021) argued that pull-out test is considered partially destructive. Although this minimally destructive technique has no impact on the structural integrity and only cause minor damage, they are sometimes referred to as non-destructive tests (NDTs). - This technique is also extremely simple, which makes it economical and adaptable to different field circumstances(Nepomuceno & Bernardo 2019; Abbas et al. 2022).	- This test is typically used to get a better understanding of the stress condition between steel and concrete. Then, the well-established finite element modelling techniques can offer a suitable prediction of structural element behaviour, which results in a decrease in the high demand for experimentation in a particular examined scenario(Abbas et al. 2022). - It does not offer the statistical method to determine other strength parameters (Al Qurishee et al. 2019). - The test cannot be performed at a later age because the steel rod must be inserted during the concrete pour (Al Qurishee et al. 2019). - Repair work is necessary since it rips out a concrete part (Al Qurishee et al. 2019).
Penetration Resistance Test	
Benefits	Limitation and difficulties
PRT is partially destructive where it causes minor localised damages to the surface of the concrete. However, it is	It is challenging to match specific concrete compressive test findings to penetrating resistance test results. They

easy to repair (Hopwood, Goff & Palle 2021). • It is quite quick and easy to complete, giving instantaneous information that might help in making prompt judgments regarding the need for maintenance or repairs(Hassani & Dackermann 2023).	do not offer through-thickness strengths for concrete bridge elements because they are near-surface tests. Compression experiments have produced positive laboratory correlations. However, it might be challenging to get these results with in-situ concrete. They can be used as markers of relatively high or low strength concretes for field tests of concrete elements(Hopwood, Goff & Palle 2021). • It shouldn't be applied within 4 inches of reinforcing steel or within 6 to 8 inches of the edge of a structural part. Despite being rapid, the test creates a little hole in the shape of a cone on the concrete. With the use of a caulk gun and masonry sealant, those can be rapidly filled (Hopwood, Goff & Palle 2021). • Absolute strength readings cannot and shouldn't be expected due to the equipment's limitations(Sharma & Jain 2022).
---	--

CHAPTER FIVE: OUTLOOK AND FUTURE WORKS

Despite the fact that corrosion monitoring is a structural engineering exercise, it cannot be separated from the scientific and technological advancements. Moreover, literature is abundant with recommendations and implications that previous research had indicated to pave the road for further improvements, development, and achievements in the field of corrosion monitoring. In this section, the main system wise recommendations and implications will be covered based on the conducted literature review:

5.1 Visual Inspection:

As mentioned previously, visual inspection has promising enhancement that can be introduced by employing new technologies, like drones, robotics, high quality cameras machine learning, AI, etc. along with the integration of visual inspection with other corrosion monitoring methods, to elevate the level of accuracy and provide more detailed evaluation for the health of the structure.

5.2 Electrochemical Corrosion Monitoring Methods:

5.2.1 Half-cell Potential Measurement (Open Circuit Potential Measurements):

Karthick et al. (2019) suggested that the potential for continuous monitoring utilizing embedded half-cell potential sensors in concrete structures is being investigated as sensor technology and data analytics progress. This advancement could lead to real-time corrosion monitoring, timely maintenance decisions, and increased structure service life specially with the current advancement in IOT, data mining and AI. Song and Saraswathy (2007) and Chaudhari and Swamy (2022) suggested that combining HCP data with other corrosion assessment techniques like as resistivity testing and corrosion rate measurement can improve corrosion assessment's prediction power and accuracy.

5.2.2 Electrical resistivity:

Robles, Yee and Kee (2022) argued that setting criteria for ER measurements that account for the impacts of corrosion rate, chloride penetration, and degree saturation at varied concrete compositions would be a complex future study, but it would fill a gap in the ER method's current applicability. In this context, Shevtsov et al. (2022) suggested that the use of auxiliary sensors to measure the changing environmental factors, like humidity and temperature, would help us correct our interpretations of the altering ER reading and ensure accurate conclusions. Furthermore, recent studies have looked at the advancement that can be introduced by using special electrodes which are able to establish optimal contact with the concrete surface, in addition to the employment of AI and data analysis algorithms to analyse the reading and improve the interpretation as discussed by Rymarczyk, Kłosowski and Kozłowski (2018).

5.2.3 Linear Polarization Resistance:

Similar to the other types of the electrochemical corrosion monitoring system, the future work is about using combination of NDT systems for better identification of corrosion as argued by Shevtsov et al. (2022), in addition to the use of AI and data analytics for better interpretation of the results.

5.2.4 Electrochemical Impedance Spectroscopy:

Rao and Ningshen (2022) argued that the utilization of a combination of methods would provide more accurate and in-depth information about the status of corrosion in RC structure. Shevtsov et al. (2022) argued that using advance materials (like piezoelectric sensors) would improve the accuracy of the ACIS measurement and provide the ability to extrapolate further information, like the corrosion starting time, its direction, as well as the weight-loss induced by corrosion. Finally, the increased use of AI and data analytics techniques is a common improvement and area of future research for the various systems.

5.2.5 The Galvanostatic Pulse Method (GPM):

As commented by de Alcantara et al. (2015), GPM and other NDT methods requires further improvement in the technology these systems are using to collect the data and analyse. It is almost imperative to say that scholars shall consider studying the use of the advance sensors as well as employing AI and data analytics techniques as an area for future research and development.

5.2.6 Electrochemical Noise Measurement (ENM):

Zaki et al. (2015) commented on the need to standardise the ENM results evaluation process. Furthermore, similar to other NDT methods, It is almost imperative to say that scholars shall consider studying the use of the advance sensors as well as employing AI and data analytics techniques as an area for future research and development.

5.3 Elastic Wave Corrosion Monitoring Methods:

5.3.1 Ultrasonic Testing (UT):

Future research should focus on developing more advanced UT systems and sensors with superior resolution to detect extremely small or early-stage corrosion and more efficient cost similar to the work carried out by Liu et al. (2016). Furthermore, With the increasing application of AI in numerous fields, incorporating AI and machine learning techniques in UT can help to automate the interpretation of results, improving the efficiency and accuracy of the process. AI can also aid in predictive maintenance, identifying patterns in corrosion progression and providing early warnings for potential structural damage (Zhang et al. 2022). Finally, using combination of different NDT systems to achieve better results would be an open field for future research.

5.3.2 Acoustic Emission (AE):

Majhi et al. (2022) suggested that incorporating active and passive wave-based systems will produce a sophisticated monitoring method. Furthermore, Verstrynge et al. (2022) commented on the improvement of AE analysis by suggesting: utilizing a suitable filtering process to increase the quality of the data used for analysis, promoting a mix of many analysis techniques to increase the overall process efficiency, and benchmarking the AE analysis results with other trusted system outputs. Moreover, due to the heavy load of data analysis and information interpretation, employing AI, machine learning and data mining tools, techniques and algorithms would introduce a noticeable improvement to overall system performance (Abarkane et al. 2023).

5.3.3 Ultrasonic Pulse Velocity Test (UPV):

The success of UPV in corrosion monitoring depends on improving how the generated data are interpreted. Several research are currently being conducted to apply sophisticated analytics and machine learning methods to increase the precision of UPV data interpretation. Machine learning algorithms could overcome the limitations of human interpretation since they can learn from enormous datasets and generate precise predictions (Concha & Oreta 2019). On the other hand, as composite materials are increasingly used in construction; it is necessary to modify current monitoring methods. Future studies should concentrate on determining how well UPV can be used to detect corrosion in these innovative materials (GODINHO et al. 2020).

5.3.4 Impact Echo (IE):

Pospisil et al. (2021) argued that combining IE with other NDT methods may improve the capacity for detection. Furthermore, Zheng et al. (2022) claimed that a larger implementation of IE in routine inspections may result from the promising ability of machine learning and

artificial intelligence to automate data interpretation. Additionally, it is possible to use sophisticated signal processing algorithms to increase precision and reduce interference from noise.

5.4 Electromagnetic Corrosion Monitoring Methods:

5.4.1 Infrared Thermography (IRT):

To improve IRT's accuracy and dependability, more research and development are needed to address its problems. The development of more complex algorithms and image processing methods and the use of AI for better thermal image interpretation may be the main focus of future work as argued by Zaki, Murdiansyah and Jusman (2021). Additionally, Kot et al. (2021) commented that combining IRT with other NDT methods may reveal additional data regarding the condition of the concrete and the degree of corrosion and it became a common practice in structural health monitoring setups.

5.4.2 Microwave Thermography (MWT):

Wu et al. (2021) commented that improvements in data processing techniques and microwave technology are enhancing MWT's capabilities. Furthermore, Gkantou et al. (2019) suggested that there is a need to improve sensors antenna and data validation techniques which would elevate the overall performance of the system. Additionally, Brinker et al. (2020) argued that AI integration has the potential to improve the effectiveness and precision of corrosion detection since machine learning algorithms may be trained to automatically interpret thermal pictures. Additionally, combining MWT with additional NDT methods might produce even more trustworthy results (Wu et al. 2021).

5.4.3 Ground Penetrating Radar (GPR):

Tesic et al. (2022) suggested that there is a need for additional studies to observe the effects of the combined parameters to produce various environmental conditions as well as to isolate the effects of each material parameter (such as the moisture content and chlorides) independently to determine their contribution to the overall change in the GPR signal. Furthermore, Wang et al. (2023) suggested that GPR can be enhanced by employing more advanced signal processing and data interpretation methods, algorithms based on machine learning and artificial intelligence. Additionally, Chang, Tsai and Shiau (2022) suggested that GPR integration with other Non-Destructive Testing (NDT) techniques could deliver more thorough and trustworthy data about the state of RC structures. Finally, it is worth highlighting that future work might concentrate on enhancing the test equipment itself by enhancing its resolution, and penetration depth. Higher-frequency antennas might be developed for improved resolution, or user-friendly software interfaces could be made to make it easier to analyse and comprehend GPR data.

5.4.4 Eddy Current Testing (ECT):

Eddy current testing, despite its limitations, is a promising tool for monitoring corrosion in RC structures. It is suggested that in the future, eddy current testing be combined with other non-destructive testing techniques to improve dependability and overcome individual method constraints. Machine learning algorithms and AI could potentially be used to improve data processing and interpretation, resulting in more accurate and automated analysis (de Alcantara et al. 2015). Additionally, he articulated that the development of sophisticated probes and sensors can improve eddy current depth penetration and make the approach even more useful for corrosion monitoring.

5.4.5 Magnetic Flux Leakage (MFL):

In order to use MFL in corrosion monitoring in the future, its current limits must be fixed, and its capabilities must be increased. Sharif et al. (2020) and many others commented on the need for looking into how to make MFL sensors more sensitive and depth-permeable, and how to employ more advanced data processing techniques like machine learning algorithms and artificial intelligence to improve the performance capabilities of the MFL testing method. Md Nor et al. (2023) argued that another viable option to improve the reliability of corrosion detection in RC structures is the integration of MFL with other non-destructive techniques like acoustic emission.

5.5 Fiber Optic Sensing Corrosion Monitoring Methods:

Alwis, Bremer and Roth (2021) highlighted that one of the most recent advancements in FOSs for structural health monitoring, or applications is the fabrication of textile, i.e., for reinforcement, with sensors already embedded within the cloth during the production process. Unlike traditional FOSs, which must be externally attached to the structure, as is the case for bridge strain monitoring, this novel sensor-embedded-reinforcement approach would allow the concrete mixture to be poured directly on top of the textile, with no additional implementations required. Such advancements would not only significantly lower staffing costs for the service provider but would also increase monitoring of deformations over a larger region of the structure, as opposed to point sensors.

Furthermore, Chen et al. (2023) commented that future research should focus on the development and implementation of fiber optic sensors for corrosion monitoring in RC structures. The current focus of research is on enhancing existing sensors and inventing new ones, particularly in terms of sensitivity and selectivity to corrosion products. Future research could include the development of specialized coatings that change their optical characteristics in response to specific forms of corrosion, as well as the use of improved data analysis techniques to give more precise and early corrosion detection(Wang, Guo, et al. 2023).

Moreover, Chen et al. (2023) pointed that a key improvement is to combine machine-learning algorithms to increase the performance of optical fiber sensor devices. additionally, artificial intelligence should be given greater attention in order to solve cross-talking problems, such as multi-parameter cross-sensitivity by merging artificial intelligence and

machine learning. However, Shevtsov et al. (2022) commented on the importance of having studies focused on generating standards to regulate the principles of the utilization of these sensors to achieve the optimum results.

In a different context, Taheri (2019) argued that the application of FOSs for pH monitoring in concrete structures is still in the early stages of development. The first strategy is based on pH-induced changes in absorbance or fluorescence intensity, while the second approach is based on the swelling effect of the pH-responsive coating (mostly hydrogels) on fiber.

5.6 Mechanical Corrosion Monitoring Methods:

The literature lacks detailed approaches for future works with respect to mechanical methods. However, as mentioned previously, mechanical methods can play a vital role by integrating these systems with other systems to improve the overall performance.

CHAPTER SIX: CONCLUSION

Corrosion in reinforced concrete (RC) structures has been highlighted as a major factor in degradation that may affect the functionality, resilience, and safety of structures. The process is frequently gradual and imperceptible until there is significant damage, which results in expensive maintenance and repair costs (Zhang & Li 2020; Van Steen & Verstrynge 2021).

In the same context, Manhes et al. (2021), Majhi et al. (2022), and many others emphasized that the need for efficient corrosion monitoring systems is heightened by the rising economic and environmental costs of maintaining and restoring RC structures. The detrimental economic and environmental effects connected with structure rehabilitation can be lessened with consistent and reliable RC structure inspection. Additionally, Tesic et al. (2022) and Van Steen and Verstrynge (2021) noted that efficient corrosion monitoring and early diagnosis can also contribute to preventative maintenance planning, potentially prolonging the service life of the structure. Therefore, it is crucial to create monitoring methods and data-driven management strategies to guarantee the secure use of essential concrete infrastructure (Verstrynge et al. 2022).

Furthermore, it has been further explained by Alsharqawi, Zayed, and Shami (2020), Alvarez, Hernández Martn, and Carraz Hernández (2023), among others, that monitoring approaches can be broadly divided into destructive and non-destructive categories. Concrete samples are removed and destroyed during destructive testing, which yields fast and precise findings. Due to their intrusiveness, lengthy procedures, and high expense, they are not suitable for routine use. However, non-destructive tests (NDT) are performed without inflicting external damage and are often based on physical characterization techniques including electromagnetic response and acoustic signals, according to Li et al. (2021). Although their results typically call for knowledge to be effective, they are less expensive, dangerous, and harmful than destructive ways (Alsharqawi, Zayed, & Shami 2020).

Furthermore, NDT technologies offer enormous promise for both new and old structures, as shown by Zaki et al. (2018). They may serve as an important tool for ensuring the quality of building materials or construction in new structures, and they may offer vital feedback for spotting and identifying deterioration in older structures. Tesic et al. (2022) also asserted that NDT technologies have become more well-liked and used in corrosion monitoring as a result of their improved sophistication, particularly their ability to present data.

From a different perspective, Hu et al. (2022) and Luo et al. (2018) highlighted that the literature further categorizes monitoring approaches as direct and indirect. Direct approaches monitor variables including corrosion potential, corrosion rate, and steel quantity using electrochemical or physical methods. In contrast, metrics related to the corrosion reaction process or corrosion-induced damage are monitored via indirect ways. In contrast to the latter, which focuses on corrosion-induced concrete cracking and steel strain redistribution, the former includes variables like chloride concentration, concrete pore solution pH values, concrete carbonation depth, and concrete resistivity.

Researchers from several nations have taken an interest in non-destructive testing (NDT) methodologies with the aim of developing and improving these techniques for concrete durability assessment (Robles, Yee & Kee 2022). In addition, Zheng et al. (2022) stated that non-destructive testing and evaluation technologies were built using a variety of engineering principles from the fields of materials science, cracks mechanisms, physical characteristics, mechanical engineering, electronics, computer and information technology, machine learning, and artificial intelligence. The primary benefit of these methods, according to Robles, Yee, and Kee (2022), is their capacity to test corrosion-related parameters rapidly, safely, and precisely. Several NDT methods have been identified, including visual inspection, electrochemical methods, elastic wave propagation methods, electromagnetic methods, optical sensing methods, and mechanical methods (Alhawati, Khan & Ashour 2020; Hassani & Dackermann 2023).

The goal of this work was to review, investigate, and analyze various corrosion monitoring techniques in order to evaluate their viability and efficiency and to suggest

further research to address the limitations of the current solutions using state-of-the-art literature review methodology. Reviewing the available literature, it was captured that the different corrosion monitoring systems respond to corrosion in various ways. Some of these systems can identify the presence of the corrosion only when its signs are there at the surface of the RC structure in the form of crack, spalling, etc. like the visual inspection methods. While others can identify the corrosion existence in early stages. However, it cannot provide further information about the size and stage of corrosion similar to the electrochemical methods. In contrast, systems like elastic wave-based systems, can provide more detailed information about corrosion and its stages. However, it might be sensitive to noise and other environmental factors which could impact its reading's reliability. On the other hand, electromagnetic methods can provide more reliable and detailed information. Nevertheless, this would be hindered by the complications of the analysis process. Similarly, fiber sensing methods can provide superior results. Nonetheless, performance is significantly influenced by installation methods, installation material properties, and optical instrument demodulation capability. In comparison to the previous systems, mechanical methods might be one of the least efficient, as its outcomes do not give a direct indication of the status of corrosion. However, the concrete quality indications resultant from these tests, would indirectly, provide an indication for the possibility of corrosion existence.

Each of these systems has advantages and disadvantages which ultimately indicates that none of these systems represents a standalone solution for corrosion monitoring at the different stage of corrosion. Thus, scholars and practitioners have been working on evaluating the feasible combinations of these systems that would provide a more comprehensive review of the corrosion status in RC structures. While other scholars and practitioners focused more on the development of the technology of these systems along with the integration with the latest machine learning, automation, data analysis and artificial intelligence development in this field. Nevertheless, the door is widely open for more active involvement and further research works in this field.

REFERENCES

- Abarkane, C., Florez-Tapia, A. M., Odriozola, J., Artetxe, A., Lekka, M., García-Lecina, E., Grande, H.-J. & Vega, J. M. (2023). Acoustic emission as a reliable technique for filiform corrosion monitoring on coated AA7075-T6: Tailored data processing. *Corrosion Science*, vol. 214, p. 110964.
- Abbas, N., Yousaf, M., Akbar, M., Saeed, M. A., Huali, P. & Hussain, Z. (2022). An Experimental Investigation and Computer Modeling of Direct Tension Pullout Test of Reinforced Concrete Cylinder. *Inventions*, vol. 7(3), p. 77.
- AbdAlla, A. N., Faraj, M. A., Samsuri, F., Rifai, D., Ali, K. & Al-Douri, Y. (2019). Challenges in improving the performance of eddy current testing: Review. *Measurement and Control*, vol. 52(1–2), pp. 46–64.
- Abu Dabous, S. & Feroz, S. (2020). Condition monitoring of bridges with non-contact testing technologies. *Automation in Construction*, vol. 116, p. 103224.
- de Alcantara, N., da Silva, F., Guimarães, M. & Pereira, M. (2015). Corrosion Assessment of Steel Bars Used in Reinforced Concrete Structures by Means of Eddy Current Testing. *Sensors*, vol. 16(1), p. 15.
- Alhamad, O. & Eid, W. (2020). Reinforced concrete problems and solutions: A literature review. *Journal of Construction Materials*, vol. 2(1).
- Alhawati, M., Khan, A. & Ashour, A. (2020). Evaluation of Steel Corrosion in Concrete Structures Using Impact-Echo Method. *Advanced Materials Research*, vol. 1158, pp. 147–164.
- Al-Sabah, S., Alam Sourav, S. N. & McNally, C. (2021). The post-installed screw pull-out test: Development of a method for assessing in-situ concrete compressive strength. *Journal of Building Engineering*, vol. 33, p. 101658.
- Alsharqawi, M., Zayed, T. & Shami, A. (2020). Ground penetrating radar-based deterioration assessment of RC bridge decks. *Construction Innovation*, vol. 20(1), pp. 1–17.
- Álvarez, J. B., Hernández Martín, E. A. & Carraz Hernández, O. R. (2023). The Georadar in the Evaluation of Reinforced Concrete Structures Affected by Corrosion. *Journal of Building Technology*, vol. 5(1).
- Alwis, L. S. M., Bremer, K. & Roth, B. (2021). Fiber Optic Sensors Embedded in Textile-Reinforced Concrete for Smart Structural Health Monitoring: A Review. *Sensors*, vol. 21(15), p. 4948.
- Amiri, A. S., Erdogmus, E. & Richter-Egger, D. (2021). A Comparison between Ultrasonic Guided Wave Leakage and Half-Cell Potential Methods in Detection of Corrosion in Reinforced Concrete Decks. *Signals*, vol. 2(3), pp. 413–433.
- Anand, N., Andrushia, Di., Paul, D. & Arulraj, P. (2021). Condition assessment and analysis of a reinforced concrete building in India: A case study. *Proceedings of the*

Institution of Civil Engineers: Forensic Engineering. ICE Publishing, vol. 174(4), pp. 89–104.

Angst, U. M. (2018). Challenges and opportunities in corrosion of steel in concrete. *Materials and Structures*, vol. 51(1), p. 4.

Arya, E. K. & Dhanya, B. S. (2021). Corrosion control of reinforced concrete structures in construction industry: A review. *IOP Conference Series: Materials Science and Engineering*, vol. 1114(1), p. 012006.

Asamoto, S., Sato, J., Okazaki, S., Chun, P. J., Sahamitmongkol, R. & Nguyen, G. H. (2021). The Cover Depth Effect on Corrosion-Induced Deterioration of Reinforced Concrete Focusing on Water Penetration: Field Survey and Laboratory Study. *Materials 2021, Vol. 14, Page 3478*. Multidisciplinary Digital Publishing Institute, vol. 14(13), p. 3478.

ASTM International. (2015). Standard Test Method for Pullout Strength of Hardened Concrete.

Augustyniak, M. & Usarek, Z. (2016). Finite Element Method Applied in Electromagnetic NDE: A Review. *Journal of Nondestructive Evaluation*, vol. 35(3), p. 39.

Baltazar-García, B. P., Baltazar-Zamora, D. F., Landa-Ruiz, L., Méndez, C. T., Solorzano, R., Márquez, S., Santiago-Hurtado, G., Moreno-Landeros, V., Croche, R. & Baltazar-Zamora, M. A. (2022). Corrosion Behavior of AISI 1018 Reinforcing Steel in Sustainable Concrete made with Sugar Cane Bagasse Ash and Recycled Aggregates Exposed in Seawater. *European Journal of Engineering and Technology Research*. European Open Science Publishing, vol. 7(6), pp. 101–107.

Baltazar-Zamora, M. A., Márquez-Montero, S., Landa-Ruiz, L., Croche, R. & López-Yza, O. (2020). Effect of the Type of Curing on the Corrosion Behavior of Concrete Exposed to Urban and Marine Environment. *European Journal of Engineering Research and Science*, vol. 5(1), pp. 91–95.

Bao, X. & Chen, L. (2011). Recent Progress in Brillouin Scattering Based Fiber Sensors. *Sensors*, vol. 11(4), pp. 4152–4187.

Barry, E. S., Merkebu, J. & Varpio, L. (2022). How to Conduct a State-of-the-Art Literature Review. *Journal of Graduate Medical Education*, vol. 14(6), pp. 663–665.

Barry, E. S., Merkebu, J. & Varpio, L. (2022). State-of-the-art literature review methodology: A six-step approach for knowledge synthesis. *Perspectives on Medical Education*, vol. 11(5), pp. 1–8.

Berkowski, P., Dmochowski, G. & Kosior-Kazberuk, M. (2013). Analysis of Structural and Material Degradation of a Car-Park's RC Bearing Structure Due to City Environmental Influences. *Procedia Engineering*, vol. 57, pp. 183–192.

Berkowski, P. & Kosior-Kazberuk, M. (2017). Material and Structural Destruction of Concrete Elements in the Industrial Environment. *Procedia Engineering*. No longer published by Elsevier, vol. 172, pp. 96–103.

- Bhagwat, Y., Nayak, G., Pandit, P., Harithakrishnan & Lakshmi, A. (2022). Corrosion Analysis of RCC Beam using Simplified FEM Model. *IOP Conference Series: Earth and Environmental Science*, vol. 1084(1), p. 012072.
- Blikharsky, Y. & Kapiika, N. (2022). ANALYSIS OF THE MOST COMMON DAMAGES IN REINFORCED CONCRETE STRUCTURES: A REVIEW. *Theory and Building Practice*, vol. 2022(1), pp. 35–42.
- Bolborea, B., Baera, C., Dan, S., Gruin, A., Burduhos-Nergis, D.-D. & Vasile, V. (2021). Concrete Compressive Strength by Means of Ultrasonic Pulse Velocity and Moduli of Elasticity. *Materials*, vol. 14(22), p. 7018.
- Bossio, A., Lignola, G. P. & Prota, A. (2018). An overview of assessment and retrofit of corroded reinforced concrete structures. *Procedia Structural Integrity*. Elsevier, vol. 11, pp. 394–401.
- Bremer, K., Wollweber, M., Weigand, F., Rahlves, M., Kuhne, M., Helbig, R. & Roth, B. (2016). Fibre Optic Sensors for the Structural Health Monitoring of Building Structures. *Procedia Technology*, vol. 26, pp. 524–529.
- Breyse, D., Balayssac, J.-P., Biondi, S., Corbett, D., Goncalves, A., Grantham, M., Luprano, V. A. M., Masi, A., Monteiro, A. V. & Sbarta, Z. M. (2019). Recommendation of RILEM TC249-ISC on non destructive in situ strength assessment of concrete. *Materials and Structures*, vol. 52(4), p. 71.
- Brinker, K., Dvorsky, M., Al Qaseer, M. T. & Zoughi, R. (2020). Review of advances in microwave and millimetre-wave NDT&E: principles and applications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 378(2182), p. 20190585.
- Cao, C. (2023). Prediction of concrete porosity using machine learning. *Results in Engineering*, vol. 17, p. 100794.
- Caprili, S., Mattei, F., Salvatore, W., Ascanio, C. & Luvarà, G. (2021). Industrial and techno-economic feasibility of concrete structures reinforced with DP rebars. *Construction and Building Materials*, vol. 283, p. 122793.
- Casprini, E. (2021). *A protocol for the assessment of corrosion effects on RC structures in a Life Cycle Engineering Framework*. UNIVERSITÀ DEGLI STUDI DI BERGAMO.
- Cavalcante, L., Araújo, E., Silva, M., Medeiros, J. L., Oliveira, V., Viera, M., Monteiro, A. & Mesquita, E. (2020). Non-destructive monitoring based on corrosion potential. *Journal of Building Pathology and Rehabilitation*, vol. 5(1), p. 11.
- Chalhoub, C., François, R. & Carcasses, M. (2020). Critical chloride threshold values as a function of cement type and steel surface condition. *Cement and Concrete Research*, vol. 134, p. 106086.
- Chang, C.-W., Tsai, C.-A. & Shiau, Y.-C. (2022). Inspection of Steel Bars Corrosion in Reinforced Concrete Structures by Nondestructive Ground Penetrating Radar. *Applied Sciences*, vol. 12(11), p. 5567.

- Chaudhari, G. & Swamy, R. (2022). A REVIEW ON CORROSION PREVENTION, REPAIR AND MAINTENANCE OF RCC STRUCTURE . *International Research Journal of Modernization in Engineering Technology and Science*, vol. 04(08).
- Chaudhari, G. V. & Swamy, R. M. (2022). An Experimental Study of Corrosion in RCC Structure: Prevention, Repair and Maintenance. *International Journal of Modern Developments in Engineering and Science*, vol. 1(8), pp. 15–20 [online]. [Accessed 21 May 2023]. Available at: <https://journal.ijmdes.com/ijmdes/article/view/73>.
- Chen, S., Wang, J., Zhang, C., Li, M., Li, N., Wu, H., Liu, Y., Peng, W. & Song, Y. (2023). Marine Structural Health Monitoring with Optical Fiber Sensors: A Review. *Sensors*, vol. 23(4), p. 1877.
- Cheyhani, M. & Chan, S. L. I. (2021). The applicability of the Wenner method for resistivity measurement of concrete in atmospheric conditions. *Case Studies in Construction Materials*. Elsevier, vol. 15, p. e00663.
- Concha, N. C. & Oreta, A. W. C. (2019). BOND STRENGTH PREDICTION MODEL OF CORRODED REINFORCEMENT IN CONCRETE USING NEURAL NETWORK. *International Journal of GEOMATE*, vol. 16(54).
- Concha, N. C. & Oreta, A. W. C. (2019). Investigation of the effects of corrosion on bond strength of steel in concrete using neural network. *The 2019 World Congress on Advances in Structural Engineering and Mechanics (ASEM19)*. Jeju Island, Korea.
- Coppola, L., Coffetti, D., Crotti, E., Gazzaniga, G. & Pastore, T. (2020). Chloride Diffusion in Concrete Protected with a Silane-Based Corrosion Inhibitor. *Materials*, vol. 13(8), p. 2001.
- Daniyal, M. & Akhtar, S. (2020). Corrosion assessment and control techniques for reinforced concrete structures: a review. *Journal of Building Pathology and Rehabilitation*, vol. 5(1), p. 1.
- Daura, L. U. (2022). *Investigation of Wireless Power Transfer-based Eddy Current Non-Destructive Testing and Evaluation*. Newcastle University .
- Demir, T., Ulucan, M. & Alyamaç, K. E. (2023). Development of Combined Methods Using Non-Destructive Test Methods to Determine the In-Place Strength of High-Strength Concretes. *Processes*, vol. 11(3), p. 673.
- Deng, Z., Huang, M., Wan, N. & Zhang, J. (2023). The Current Development of Structural Health Monitoring for Bridges: A Review. *Buildings*, vol. 13(6), p. 1360.
- Dhungana, A., Mishra, A. K. & Aithal, P. (2022). Analysis of the Variation in Different Nondestructive Testing and Standards. *Journal of Advanced Research in Civil and Environmental Engineering*, vol. 9(1 & 2), pp. 1–11.
- Diaferio, M. & Varona, F. B. (2022). The Performance of Empirical Laws for Rebound Hammer Tests on Concrete Structures. *Applied Sciences*, vol. 12(11), p. 5631.

- Dogan, G., Hakan Arslan, M. & Ilki, A. (2023). Detection of damages caused by earthquake and reinforcement corrosion in RC buildings with Deep Transfer Learning. *Engineering Structures*, vol. 279, p. 115629.
- Duvnjak, I., Klepo, I., Serdar, M. & Damjanović, D. (2021). Damage Assessment of Reinforced Concrete Elements Due to Corrosion Effect Using Dynamic Parameters: A Review. *Buildings*, vol. 11(10), p. 425.
- Eldeen, N. & Nassar, M. A. A. (2021). Reinforcement corrosion in reinforced concrete Structures: Classification and overview. *International Journal of Advanced Engineering, Sciences and Applications*. London Tech Press, vol. 2(1), pp. 19–24.
- Fan, L. & Shi, X. (2022). Techniques of corrosion monitoring of steel rebar in reinforced concrete structures: A review. *Structural Health Monitoring*, vol. 21(4), pp. 1879–1905.
- Farhangdoust, S. & Mehrabi, A. (2019). Health Monitoring of Closure Joints in Accelerated Bridge Construction: A Review of Non-Destructive Testing Application. *Journal of Advanced Concrete Technology*, vol. 17, pp. 381–404.
- Faritov, A. T., Rozhdestvenskii, Yu. G., Yamshchikova, S. A., Minnikhanova, E. R. & Tyusenkov, A. S. (2016). Improvement of the linear polarization resistance method for testing steel corrosion inhibitors. *Russian Metallurgy (Metally)*, vol. 2016(11), pp. 1035–1041.
- Fernandez, A. G. & Mallco, A. (2018). Corrosion Monitoring by Electrochemical Impedance Spectroscopy Test of LowCr Alloy Steel T22 and High-Ni Alloy HR224 in Nitrate Molten Salt. *Insights in Analytical Electrochemistry*, vol. 4.
- Figueira, R. (2017). Electrochemical Sensors for Monitoring the Corrosion Conditions of Reinforced Concrete Structures: A Review. *Applied Sciences*, vol. 7(11), p. 1157.
- Fornasari, G., Capozzoli, L. & Rizzo, E. (2023). Combined GPR and Self-Potential Techniques for Monitoring Steel Rebar Corrosion in Reinforced Concrete Structures: A Laboratory Study. *Remote Sensing*, vol. 15(8), p. 2206.
- Frølund, T., Jensen, F. M. & Bassler, R. (2002). DETERMINATION OF REINFORCEMENT CORROSION RATE BY MEANS OF THE GALVANOSTATIC PULSE TECHNIQUE . *First International Conference on Bridge Maintenance, Safety and Management*. Barcelona: IABMAS.
- Fukuyama, T., Nagai, H. & Noguchi, T. (2009). Corrosion Monitoring of Reinforcing Bars by Electrochemical Noise Measurement . *4th International Conference on Structural Health Monitoring of Intelligent Infrastructure* . Zurich, Switzerland.
- Galindez-Jamioy, C. A. & López-Higuera, J. M. (2012). Brillouin Distributed Fiber Sensors: An Overview and Applications. *Journal of Sensors*, vol. 2012, pp. 1–17.
- García-Contreras, J., Gaona-Tiburcio, C., López-Cazares, I., Sánchez-Díaz, G., Ibarra Castillo, J. C., Jáquez-Muñoz, J., Nieves-Mendoza, D., Maldonado-Bandala, E., Olguín-Coca, J., López-León, L. D. & Almeraya-Calderón, F. (2021). Effect of Cathodic Protection on Reinforced Concrete with Fly Ash Using Electrochemical Noise. *Materials*, vol. 14(9), p. 2438.

García-Peñalvo, F. J. (2022). Desarrollo de estados de la cuestión robustos: Revisiones Sistemáticas de Literatura. *Education in the Knowledge Society (EKS)*, vol. 23, p. e28600.

Ge, B. & Kim, S. (2021). Probabilistic service life prediction updating with inspection information for RC structures subjected to coupled corrosion and fatigue. *Engineering Structures*, vol. 238, p. 112260.

Gholizadeh, S. (2016). A review of non-destructive testing methods of composite materials. *Procedia Structural Integrity*, pp. 50–57.

Gkantou, M., Muradov, M., Kamaris, G. S., Hashim, K., Atherton, W. & Kot, P. (2019). Novel Electromagnetic Sensors Embedded in Reinforced Concrete Beams for Crack Detection. *Sensors*, vol. 19(23), p. 5175.

GODINHO, J. P., DE SOUZA JÚNIOR, T. F., MEDEIROS, M. H. F. & SILVA, M. S. A. (2020). Factors influencing ultrasonic pulse velocity in concrete. *Revista IBRACON de Estruturas e Materiais*, vol. 13(2), pp. 222–247.

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*, vol. 13(3), p. 765.

Goyal, A., Pouya, H. S., Ganjian, E. & Claisse, P. (2018). A Review of Corrosion and Protection of Steel in Concrete. *Arabian Journal for Science and Engineering*. Springer Verlag, vol. 43(10), pp. 5035–5055.

Grant, M. J. & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, vol. 26(2), pp. 91–108.

Guo, J., Sun, W., Xu, Y., Lin, W. & Jing, W. (2022). Damage Mechanism and Modeling of Concrete in Freeze–Thaw Cycles: A Review. *Buildings*, vol. 12(9), p. 1317.

Ha, N., Lee, H.-S. & Lee, S. (2021). Development of a Wireless Corrosion Detection System for Steel-Framed Structures Using Pulsed Eddy Currents. *Sensors*, vol. 21(24), p. 8199.

Halleman, N., Howey, D., Battistel, A., Saniee, N. F., Scarpioni, F., Wouters, B., La Mantia, F., Hubin, A., Widanage, W. D. & Lataire, J. (2023). Electrochemical impedance spectroscopy beyond linearity and stationarity - a critical review.

Hammad, D. B., Shafiq, N. & Nuruddin, M. F. (2018). Vectors of Defects in Reinforced Concrete Structures in Onshore Oil and Gas Process Plants. *Advances in Civil Engineering*. Hindawi Limited, vol. 2018.

Hariri-Ardebili, M. A., Sanchez, L. & Rezakhani, R. (2020). Aging of Concrete Structures and Infrastructures: Causes, Consequences, and Cures (C³). *Advances in Materials Science and Engineering*, vol. 2020, pp. 1–3.

Haris, N. & Gadve, S. (2022). Effect of Corrosion on Bond Strength and Development Length of Reinforcing Bar in Epoxy-Grouted Nut Coupler. *ACI Materials Journal*, vol. 119(5).

Harsimran, S., Santosh, K. & Rakesh, K. (2021). OVERVIEW OF CORROSION AND ITS CONTROL: A CRITICAL REVIEW. *Proceedings on Engineering Sciences*, vol. 3(1), pp. 13–24.

Hassani, S. & Dackermann, U. (2023). A Systematic Review of Advanced Sensor Technologies for Non-Destructive Testing and Structural Health Monitoring. *Sensors*, vol. 23(4), p. 2204.

Herrera Hernández, H., M. Ruiz Reynoso, A., C. Trinidad González, J., O. González Morán, C., G. Miranda Hernández, J., Mandujano Ruiz, A., Morales Hernández, J. & Orozco Cruz, R. (2020). ‘Electrochemical impedance spectroscopy (eis): a review study of basic aspects of the corrosion mechanism applied to steels’. , in *Electrochemical Impedance Spectroscopy*. IntechOpen.

Hopwood, T., Goff, C. & Palle, S. (2021). Assessment of Deteriorated Structural Concrete to Provide Durable Repairs. *Kentucky Transportation Center Research Report*.

Hu, J. Y., Zhang, S. S., Chen, E. & Li, W. G. (2022). A review on corrosion detection and protection of existing reinforced concrete (RC) structures. *Construction and Building Materials*, vol. 325, p. 126718.

Ichi, E. & Dorafshan, S. (2022). Effectiveness of infrared thermography for delamination detection in reinforced concrete bridge decks. *Automation in Construction*, vol. 142, p. 104523.

Ismail Abdel Rahman Mohamed Abdel Rahman. (2007). *Effect of Vibrations on Concrete Strength*. University of Khartoum.

Ismail, F. I., Abbas, Y. M., Shafiq, N., Fares, G., Osman, M., Hussain, L. A. & Khan, M. I. (2021). Investigation of the Impact of Graphene Nanoplatelets (GnP) on the Bond Stress of High-Performance Concrete Using Pullout Testing. *Materials*. MDPI, vol. 14(22), p. 7054.

James, A., Bazarchi, E., Chiniforush, A. A., Panjebashi Aghdam, P., Hosseini, M. R., Akbarnezhad, A., Martek, I. & Ghodoosi, F. (2019). Rebar corrosion detection, protection, and rehabilitation of reinforced concrete structures in coastal environments: A review. *Construction and Building Materials*, vol. 224, pp. 1026–1039.

Jeon, D., Jung, J., Park, J., Min, J., Oh, J. E., Moon, J., Lee, J.-S. & Yoon, S. (2022). Predicting airborne chloride deposition in marine bridge structures using an artificial neural network model. *Construction and Building Materials*, vol. 337, p. 127623.

Kabir Sadeghi, Muhammad Khidre Musa & Hazar M. Nassrullah. (2019). CORROSION PROBLEMS IN RC STRUCTURES: AN OVERVIEW OF CAUSES, MECHANISM, EFFECTS, CONTROLS AND EVALUATION. *Academic Research International*, vol. 10(2).

Kannan, G., Manoharan, N. & Venkataraman, B. (2015). A Heuristic Non Destructive Evaluation Technique For Rebar Corrosion of Marine Structures based on the synergy of Infrared Thermography, Signal and Image Processing. *Proceedings of the 2015 Asia International Conference on Quantitative InfraRed Thermography*. QIRT Council.

- Karthick, S., Muralidharan, S., Lee, H.-S., Kwon, S.-J. & Saraswathy, V. (2019). Reliability and long-term evaluation of GO-MnO₂ nano material as a newer corrosion monitoring sensor for reinforced concrete structures. *Cement and Concrete Composites*, vol. 100, pp. 74–84.
- Kasassbeh*, S. Al, Tamseh*, A. Al & Kharabsheh, E. Al. (2020). Modern Techniques for the Restoration and Rehabilitation of Concrete Structures. *International Journal of Recent Technology and Engineering (IJRTE)*. Blue Eyes Intelligence Engineering and Sciences Engineering and Sciences Publication - BEIESP, vol. 9(1), pp. 1826–1833.
- Kaur, J. & Saxena, A. (2023). ‘An account on destructive and nondestructive methods of corrosion measurements’. , in *Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring*. Elsevier, pp. 281–292.
- Kawasaki, Y., Fukui, S. & Fukuyama, T. (2022). Phenomenological process of rebar corrosion in reinforced concrete evaluated by acoustic emission and electrochemical noise. *Construction and Building Materials*, vol. 352, p. 128829.
- Keo, S. A., Brachelet, F., Defer, D. & Breaban, F. (2022). Detection of Concrete Cover of Reinforcements in Reinforced Concrete Wall by Microwave Thermography with Transmission Approach. *Applied Sciences*, vol. 12(19), p. 9865.
- Khan, M. I., Castel, A. & Gilbert, R. I. (2018). Corrosion-induced cracking and bond strength in reinforced concrete: A review. . *Engineering Structures*.
- Komary, M., Komarizadehasl, S., Tošić, N., Segura, I., Lozano-Galant, J. A. & Turmo, J. (2023). Low-Cost Technologies Used in Corrosion Monitoring. *Sensors*, vol. 23(3), p. 1309.
- Kot, P., Muradov, M., Gkantou, M., Kamaris, G. S., Hashim, K. & Yeboah, D. (2021). Recent Advancements in Non-Destructive Testing Techniques for Structural Health Monitoring. *Applied Sciences*, vol. 11(6), p. 2750.
- Krentowski, J. R. (2021). Assessment of Destructive Impact of Different Factors on Concrete Structures Durability. *Materials*, vol. 15(1), p. 225.
- Landa-Ruiz, L., Baltazar-Zamora, M. A., Bosch, J., Ress, J., Santiago-Hurtado, G., Moreno-Landeros, V. M., Márquez-Montero, S., Méndez, C. T., Borunda, A., Juárez-Alvarado, C. A., Mendoza-Rangel, J. M. & Bastidas, David. M. (2021). Electrochemical Corrosion of Galvanized Steel in Binary Sustainable Concrete Made with Sugar Cane Bagasse Ash (SCBA) and Silica Fume (SF) Exposed to Sulfates. *Applied Sciences*, vol. 11(5), p. 2133.
- Li, B., Li, S., Zhang, G., Ying, H., Xia, Q. & Liu, S. (2023). Grading assessment of steel bar corrosion in concrete structures based on naive Bayesian model and spontaneous magnetic flux leakage effect. *Journal of Engineering and Applied Science*, vol. 70(1), p. 3.
- Li, D., Zhou, J. & Ou, J. (2021). Damage, nondestructive evaluation and rehabilitation of FRP composite-RC structure: A review. *Construction and Building Materials*, vol. 271, p. 121551.

- Li, J., Xiong, J., Fan, Z., Chen, M., Sun, L., Zhu, C., Liu, W., Zheng, H. & Li, W. (2023). Mechanistic study of macrocell effect on corrosion initiation and propagation of reinforcement in submarine immersed tunnel. *Cement and Concrete Composites*, vol. 136, p. 104890.
- Li, P., Yu, H., Li, Z., Zhang, B., Wu, T., Pu, Z. & Wang, S. (2023). Corrosion detection of reinforced concrete structures based on microwave nondestructive technique. *AIP Advances*, vol. 13(2), p. 025346.
- Li, W., Li, Y., Tan, J., Abidin, I. M. Z., Hu, J., Chen, Z. & Wu, Y. (2019). A Millimetre-wave Probe for Fast Screening and Evaluation of Corrosion in Planar Conductors: Numerical Simulations. *IOP Conference Series: Materials Science and Engineering*, vol. 554(1), p. 012003.
- Li, Z., Jin, Z., Wang, P. & Zhao, T. (2021). Corrosion mechanism of reinforced bars inside concrete and relevant monitoring or detection apparatus: A review. *Construction and Building Materials*, vol. 279, p. 122432.
- Li, Z., Jin, Z., Xu, X., Zhao, T., Wang, P. & Li, Z. (2020). Combined application of novel electromagnetic sensors and acoustic emission apparatus to monitor corrosion process of reinforced bars in concrete. *Construction and Building Materials*, vol. 245, p. 118472.
- Liu, D., Gong, C., Tang, Y., Jian, Y., Cao, K. & Chen, H. (2022). Evaluation of Corrosion Damage in Sulfate-Attacked Concrete by CT, Ultrasonic Pulse Velocity Testing and AHP Methods. *Sensors*, vol. 22(8), p. 3037.
- Liu, D., Wang, C., Gonzalez-Libreros, J., Guo, T., Cao, J., Tu, Y., Elfgren, L. & Sas, G. (2023). A review of concrete properties under the combined effect of fatigue and corrosion from a material perspective. *Construction and Building Materials*, vol. 369, p. 130489.
- Liu, J., Zhang, W., Li, Z., Jin, H. & Tang, L. (2021). Influence of deicing salt on the surface properties of concrete specimens after 20 years. *Construction and Building Materials*, vol. 295, p. 123643.
- Liu, L., Zheng, D., Zhou, J., Yang, J. & Zhang, H. (2020). Parameters That Influence Corrosion Detection in Reinforced Concrete Based on Eddy Current Thermography. *Advances in Civil Engineering*, vol. 2020, pp. 1–9.
- Liu, X., Qin, L. & Huang, B. (2018). Ultrasonic guided wave for monitoring corrosion of steel bar. *IOP Conference Series: Earth and Environmental Science*, vol. 108, p. 022071.
- Liu, X., Qin, L., Ni, X., Zhu, X., Huang, S. & Cheng, X. (2016). Monitoring corrosion of steel bar using ultrasonic guided wave. *4th International Conference on Machinery, Materials and Information Technology Applications (ICMMITA 2016)*. Atlantis Press.
- Liu, Y.-L., Shi, J.-J., Huang, J.-Q., Wei, G.-S. & Wu, Z.-X. (2019). Grouting Defect Detection of Lapped Bar Connections Based on Impact-Echo Method. *Shock and Vibration*, vol. 2019, pp. 1–14.
- Lliso-Ferrando, J. R., Gasch, I., Martínez-Ibernón, A. & Valcuende, M. (2022). Effect of macrocell currents on rebar corrosion in reinforced concrete structures exposed to a marine environment. *Ocean Engineering*, vol. 257, p. 111680.

- Lollini, F. & Redaelli, E. (2021). Carbonation of blended cement concretes after 12 years of natural exposure. *Construction and Building Materials*, vol. 276, p. 122122.
- Luo, D., Li, Y., Li, J., Lim, K.-S., Nazal, N. A. M. & Ahmad, H. (2018). A Recent Progress of Steel Bar Corrosion Diagnostic Techniques in RC Structures. *Sensors*, vol. 19(1), p. 34.
- Luo, J., Asamoto, S. & Nagai, K. (2023). Mesoscale simulation of compression-induced cracking and failure of ASR-damaged concrete with stirrup confinement. *Engineering Fracture Mechanics*, vol. 277, p. 108977.
- Ma, C., Wang, Z., Behnamian, Y., Gao, Z., Wu, Z., Qin, Z. & Xia, D. H. (2019). Measuring atmospheric corrosion with electrochemical noise: A review of contemporary methods. *Measurement*. Elsevier, vol. 138, pp. 54–79.
- Majhi, S., Asilo, L. K., Mukherjee, A., George, N. V. & Uy, B. (2022). Multimodal Monitoring of Corrosion in Reinforced Concrete for Effective Lifecycle Management of Built Facilities. *Sustainability*, vol. 14(15), p. 9696.
- Mangat, P. S., Ojedokun, O. O. & Lambert, P. (2021). Chloride-initiated corrosion in alkali activated reinforced concrete. *Cement and Concrete Composites*, vol. 115, p. 103823.
- Manhães, P. M. B., Júnior, J. T. A., Chen, G., Anderson, N. L. & dos Santos, A. B. (2021). Ground penetrating radar for assessment of reinforced concrete wastewater treatment plant. *Journal of Civil Structural Health Monitoring*, vol. 11(1), pp. 1–14.
- Marcantonio, V., Monarca, D., Colantoni, A. & Cecchini, M. (2019). Ultrasonic waves for materials evaluation in fatigue, thermal and corrosion damage: A review. *Mechanical Systems and Signal Processing*, vol. 120, pp. 32–42.
- Martin, U., Ress, J., Bosch, J. & Bastidas, D. M. (2020). Stress corrosion cracking mechanism of AISI 316LN stainless steel rebars in chloride contaminated concrete pore solution using the slow strain rate technique. *Electrochimica Acta*. Pergamon, vol. 335, p. 135565.
- Martínez Ibernón, A., Lliso Ferrando, J., Gasch, I. & Valcuende, M. (2022). Estimation of Humidity Variation and Electric Resistivity in Hardened Concrete by Means of a Stainless Steel Voltammetric Sensor. *Sensors*, vol. 22(19), p. 7279.
- Mattsson, E. (1999). *Basic Corrosion Technology for Scientists and Engineers*. 2nd edn. CRC Press.
- May, Z., Alam, M. K. & Nayan, N. A. (2022). Recent Advances in Nondestructive Method and Assessment of Corrosion Undercoating in Carbon–Steel Pipelines. *Sensors*, vol. 22(17), p. 6654.
- Md Nor, N., Abdullah, S., Mohamad Halim, M. A. H. & Arifin, A. (2023). Evaluation of the Behaviour of Steel Bar in the Concrete under Cyclic Loading Using Magnetic Flux Leakage and Acoustic Emission Techniques. *Materials*, vol. 16(6), p. 2172.
- Melchers, R. E. & Chaves, I. A. (2020). Reinforcement Corrosion in Marine Concretes 2. Long-Term Effects. *ACI Materials Journal*, vol. 117(2).

Michael, M., Kennedy, C. & Oba, A. L. (2021). Wenner Probe Technique Application in Electrical Resistivity and Corrosion Potential Measurements of Concrete Induced Chloride threshold Mechanism. *Saudi Journal of Engineering and Technology*, vol. 6(8).

Mills, D., Lambert, P. & Yang, S. (2021). Electrochemical Noise Measurement to Assess Corrosion of Steel Reinforcement in Concrete. *Materials*, vol. 14(18), p. 5392.

Miró, M., Eiras, J. N., Poveda, P., Climent, M. Á. & Ramis, J. (2021). Detecting cracks due to steel corrosion in reinforced cement mortar using intermodulation generation of ultrasonic waves. *Construction and Building Materials*, vol. 286, p. 122915.

Mukhti, J. A., Robles, K. P. V., Lee, K.-H. & Kee, S.-H. (2023). Evaluation of Early Concrete Damage Caused by Chloride-Induced Steel Corrosion Using a Deep Learning Approach Based on RNN for Ultrasonic Pulse Waves. *Materials*, vol. 16(9), p. 3502.

Na, S. & Paik, I. (2019). Application of Thermal Image Data to Detect Rebar Corrosion in Concrete Structures. *Applied Sciences*, vol. 9(21), p. 4700.

Nanayakkara, O., Najm, H. M. & Sabri, M. M. S. (2022). Effect of Using Steel Bar Reinforcement on Concrete Quality by Ultrasonic Pulse Velocity Measurements. *Materials*, vol. 15(13), p. 4565.

Ndagi, A., Umar, A. A., Hejazi, F. & Jaafar, M. S. (2019). Non-destructive assessment of concrete deterioration by ultrasonic pulse velocity: A review. *IOP Conference Series: Earth and Environmental Science*, vol. 357(1), p. 012015.

Negi, P., Kromanis, R., Dorée, A. G. & Wijnberg, K. M. (2023). Structural health monitoring of inland navigation structures and ports: a review on developments and challenges. *Structural Health Monitoring*, p. 147592172311707.

Nepomuceno, M. C. S. & Bernardo, L. F. A. (2019). Evaluation of Self-Compacting Concrete Strength with Non-Destructive Tests for Concrete Structures. *Applied Sciences*, vol. 9(23), p. 5109.

Nikoo, M., Sadowski, Ł. & Nikoo, M. (2017). Prediction of the Corrosion Current Density in Reinforced Concrete Using a Self-Organizing Feature Map. *Coatings*, vol. 7(10), p. 160.

NISHIDA, T., OTSUKI, N., HAMAMOTO, J., BACCAY, M. & CHIN, K. (2005). TEMPERATURE DEPENDENCY OF CORROSION RATE OF STEEL BARS IN CONCRETE INFLUENCED BY MATERIAL SEGREGATION. *Doboku Gakkai Ronbunshu*, vol. 2005(781), pp. 781_75-781_87.

Okenyi, A. V. & Alawode, J. K. (2021). IMPACT OF CORROSION MONITORING TECHNIQUES ON DURABILITY ASSESSMENT IN REINFORCED CONCRETE: A REVIEW. *ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT*, vol. 17(2), pp. 141–164.

Pagadala, M., Mundra, S. & Bansal, S. (2022). Corrosion monitoring techniques for concrete in corrosive environments. *Corrosion Reviews*, vol. 40(5), pp. 409–425.

Pant, U. & Shrestha, J. K. (2022). Bridge Deck Quality Indexing based on Non-Destructive Tests. *Proceedings of 12th IOE Graduate Conference*.

- PCA. (2002). *Types and Causes of Concrete Deterioration*.
- Peansupap, V. & Ly, R. (2015). Evaluating the Impact Level of Design Errors in Structural and Other Building Components in Building Construction Projects in Cambodia. *Procedia Engineering*, vol. 123, pp. 370–378.
- Pfändler, P. ;, Bodie, K. ;, Angst, U. ; & Siegwart, R. (2019). Flying corrosion inspection robot for corrosion monitoring of civil structures – First results. *SMAR 2019 - Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures - Program*. SMAR, p. We.4.A.6.
- Pospisil, K., Manychova, M., Stryk, J., Korenska, M., Matula, R. & Svoboda, V. (2021). Diagnostics of Reinforcement Conditions in Concrete Structures by GPR, Impact-Echo Method and Metal Magnetic Memory Method. *Remote Sensing*, vol. 13(5), p. 952.
- Quraishi, M., Nayak, D., Kumar, R. & Kumar, V. (2017). Corrosion of Reinforced Steel in Concrete and Its Control: An overview. *Journal of Steel Structures & Construction*. OMICS Publishing Group, vol. 03(01).
- Al Qurishee, M., Wu, W., Atolagbe, B., El Said, S. & Ghasemi, A. (2019). Non-Destructive Test Application in Civil Infrastructure. *International Research Journal of Engineering and Technology (IRJET)*, vol. 6(12).
- Raczkiwicz, W. & Wójcicki, A. (2020). Temperature Impact on the Assessment of Reinforcement Corrosion Risk in Concrete by Galvanostatic Pulse Method. *Applied Sciences*, vol. 10(3), p. 1089.
- Rajendran, V., Prathuru, A., Fernandez, C. & Faisal, N. H. (2023). Corrosion monitoring at the interface using sensors and advanced sensing materials: methods, challenges and opportunities. *Corrosion Engineering, Science and Technology*, vol. 58(3), pp. 281–321.
- Ramani, V. & Kuang, K. S. C. (2021). Monitoring of rebar corrosion in concrete structures using a lens-based plastic optical fiber (LPOF) sensor. *Construction and Building Materials*. Elsevier, vol. 276, p. 122129.
- Rao, Ch. J. & Ningshen, S. (2022). High-temperature electrochemical corrosion evaluation of 2.25Cr–1Mo alloy in eutectic LiCl–KCl molten salt. *Corrosion Engineering, Science and Technology*, vol. 57(1), pp. 66–73.
- Rao, R. K. & Sasmal, S. (2022). Nanoengineered smart cement composite for electrical impedance-based monitoring of corrosion progression in structures. *Cement and Concrete Composites*. Elsevier, vol. 126, p. 104348.
- Roberge, P. (2008). *Corrosion Engineering Principles and Practice*. The McGraw-Hill Companies, Inc.
- Robles, K. P. V., Yee, J.-J. & Kee, S.-H. (2022). Electrical Resistivity Measurements for Nondestructive Evaluation of Chloride-Induced Deterioration of Reinforced Concrete—A Review. *Materials*, vol. 15(8), p. 2725.

Robuschi, S., Sumearll, J., Fernandez, I. & Lundgren, K. (2021). Bond of naturally corroded, plain reinforcing bars in concrete. *Structure and Infrastructure Engineering*, vol. 17(6), pp. 792–808.

Rodrigues, R., Gaboreau, S., Gance, J., Ignatiadis, I. & Betelu, S. (2021). Reinforced concrete structures: A review of corrosion mechanisms and advances in electrical methods for corrosion monitoring. *Construction and Building Materials*, vol. 269, p. 121240.

Rymarczyk, T., Kłosowski, G. & Kozłowski, E. (2018). A Non-Destructive System Based on Electrical Tomography and Machine Learning to Analyze the Moisture of Buildings. *Sensors*, vol. 18(7), p. 2285.

Sakiyama, F. I. H., Lehmann, F. & Garrecht, H. (2021). Structural health monitoring of concrete structures using fibre-optic-based sensors: a review. *Magazine of Concrete Research*, vol. 73(4), pp. 174–194.

SANO, S., MIZOBUCHI, T., SHIMBO, H., OZEKI, T. & NOJIMA, J. (2022). Study on Applicability of Detection of Internal Cracks by Impact Echo Using Machine Learning. *The International Symposium on Nondestructive Testing in Civil Engineering*.

Sato, S., Masuda, Y. & Kakegawa, M. (2020). Long-term Performance of Repairs to Reinforced Concrete Exposed to Coastal Conditions. *XV International Conference on Durability of Building Materials and Components (DBMC 2020)*. International Center for Numerical Methods in Engineering, pp. 1503–1510.

Scherr, J. F. & Grosse, C. U. (2021). Delamination detection on a concrete bridge deck using impact echo scanning. *Structural Concrete*, vol. 22(2), pp. 806–812.

Ben Seghier, M. E. A., Keshtegar, B. & Mahmoud, H. (2021). Time-Dependent Reliability Analysis of Reinforced Concrete Beams Subjected to Uniform and Pitting Corrosion and Brittle Fracture. *Materials*, vol. 14(8), p. 1820.

Sharif, N. A., Ramli, R., Nuawi, M. Z. & Mohamed, A. Z. (2020). Theory and Development of Magnetic Flux Leakage Sensor for Flaws Detection: A Review. *Jurnal Kejuruteraan*, vol. 32(3), pp. 385–395.

Sharma, P. & Jain, A. K. (2022). Experimental Investigation on a Concrete Sample using Red Mud as a Partial Replacement of Portland Cement. *Research Journal of Engineering Technology and Medical Sciences*, vol. 5(3).

Sharma, S., Arora, H. C., Kumar, A., Kontoni, D.-P. N., Kapoor, N. R., Kumar, K. & Singh, A. (2023). Computational Intelligence-Based Structural Health Monitoring of Corroded and Eccentrically Loaded Reinforced Concrete Columns. *Shock and Vibration*, vol. 2023, pp. 1–21.

Shevtsov, D., Cao, N. L., Nguyen, V. C., Nong, Q. Q., Le, H. Q., Nguyen, D. A., Zartsyn, I. & Kozaderov, O. (2022). Progress in Sensors for Monitoring Reinforcement Corrosion in Reinforced Concrete Structures—A Review. *Sensors 2022, Vol. 22, Page 3421*. Multidisciplinary Digital Publishing Institute, vol. 22(9), p. 3421.

Shi, Caijun. & Mo, Y. L. (2008). High-performance construction materials : science and applications. World Scientific, p. 431.

- da Silva, M. R., Rohden, A. B., Mesquita, E. F. T. & Garcez, M. R. (2020). Influence of concrete cover in the service life of a newly built reinforced concrete structure: a case study. *Journal of Building Pathology and Rehabilitation*, vol. 5(1), p. 9.
- Solanki, P., Xie, H., Awaitey, J. & Reddy, T. (2023). *State-of-the-Practice Review of Field-Curing Methods for Evaluating the Strength of Concrete Test Specimens*. Rantoul.
- Soman, R., Wee, J. & Peters, K. (2021). Optical Fiber Sensors for Ultrasonic Structural Health Monitoring: A Review. *Sensors*, vol. 21(21), p. 7345.
- Song, H.-W. & Saraswathy, V. (2007). Corrosion Monitoring of Reinforced Concrete Structures - A Review. *International Journal of Electromechanical Science* , vol. 2.
- Sossa, V., Pérez-Gracia, V., González-Drigo, R. & A. Rasol, M. (2019). Lab Non Destructive Test to Analyze the Effect of Corrosion on Ground Penetrating Radar Scans. *Remote Sensing*, vol. 11(23), p. 2814.
- Van Steen, C. & Verstrynge, E. (2021). Degradation Monitoring in Reinforced Concrete with 3D Localization of Rebar Corrosion and Related Concrete Cracking. *Applied Sciences*, vol. 11(15), p. 6772.
- Taheri, S. (2019). A review on five key sensors for monitoring of concrete structures. *Construction and Building Materials*, vol. 204, pp. 492–509.
- Tamhane, D., Thalapil, J., Banerjee, S. & Tallur, S. (2022). Performance evaluation of electro-mechanical impedance based state of health estimation of sacrificial anodes in reinforced concrete structures. *Construction and Building Materials*, vol. 342, p. 128034.
- Tang, F., Zhou, G., Li, H.-N. & Verstrynge, E. (2021). A review on fiber optic sensors for rebar corrosion monitoring in RC structures. *Construction and Building Materials*, vol. 313, p. 125578.
- Tesic, K., Baricevic, A., Serdar, M. & Gucunski, N. (2022). Characterization of ground penetrating radar signal during simulated corrosion of concrete reinforcement. *Automation in Construction*. Elsevier, vol. 143, p. 104548.
- Trach, R., Ryzhakova, G., Trach, Y., Shpakov, A. & Tyvoniuk, V. (2023). Modeling the Cause-and-Effect Relationships between the Causes of Damage and External Indicators of RC Elements Using ML Tools. *Sustainability*, vol. 15(6), p. 5250.
- Uma Maheshwari, K. & Venkat Rao, N. (2022). Effect of Cementious Materials on Corrsion in Carbonated Concrete. *IOP Conference Series: Earth and Environmental Science*, vol. 1086(1), p. 012003.
- 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*, vol. 349, p. 128732.
- Wang, H., Guo, J.-K., Mo, H., Zhou, X. & Han, Y. (2023). Fiber Optic Sensing Technology and Vision Sensing Technology for Structural Health Monitoring. *Sensors*, vol. 23(9), p. 4334.

- Wang, J., Wang, Q., Zhao, Y., Li, P., Ji, T., Zou, G., Qiao, Y., Zhou, Z., Wang, G. & Song, D. (2023). Research Progress of Macrocell Corrosion of Steel Rebar in Concrete. *Coatings*, vol. 13(5), p. 853.
- Wang, Z., Wang, J., Chen, K., Li, Z., Xu, J., Li, Y. & Sui, Q. (2023). Unsupervised learning method for rebar signal suppression and defect signal reconstruction and detection in ground penetrating radar images. *Measurement*, vol. 211, p. 112652.
- Wan-Wendner, R. (2018). Aging concrete structures: A review of mechanics and concepts. *Bodenkultur*. Sciendo, vol. 69(3), pp. 175–199.
- Wicherts, J. M. (2016). Peer Review Quality and Transparency of the Peer-Review Process in Open Access and Subscription Journals. *PLOS ONE*, vol. 11(1), p. e0147913.
- Wu, F., Chen, X. & Chen, J. (2023). Abrasion resistance enhancement of concrete using surface treatment methods. *Tribology International*, vol. 179, p. 108180.
- Wu, R., Zhang, H., Yang, R., Chen, W. & Chen, G. (2021). Nondestructive Testing for Corrosion Evaluation of Metal under Coating. *Journal of Sensors*, vol. 2021, pp. 1–16.
- Yang, Y., Chai, W., Liu, D., Zhang, W., Lu, J. & Yang, Z. (2021). An Impact-Echo Experimental Approach for Detecting Concrete Structural Faults. *Advances in Civil Engineering*, vol. 2021, pp. 1–8.
- Ye, X. W., Su, Y. H. & Han, J. P. (2014). Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review. *The Scientific World Journal*, vol. 2014, pp. 1–11.
- Zaki, A., Chai, H., Aggelis, D. & Alver, N. (2015). Non-Destructive Evaluation for Corrosion Monitoring in Concrete: A Review and Capability of Acoustic Emission Technique. *Sensors*, vol. 15(8), pp. 19069–19101.
- Zaki, A., Megat Johari, M. A., Wan Hussin, W. M. A. & Jusman, Y. (2018). Experimental Assessment of Rebar Corrosion in Concrete Slab Using Ground Penetrating Radar (GPR). *International Journal of Corrosion*, vol. 2018, pp. 1–10.
- Zaki, A., Murdiansyah, L. & Jusman, Y. (2021). Cracks Evaluation of Reinforced Concrete Structure: A Review. *Journal of Physics: Conference Series*, vol. 1783(1), p. 012091.
- Zarrabi, N., Moghim, M. N. & Eftekhari, M. R. (2021). Effect of hydraulic parameters on abrasion erosion of fiber reinforced concrete in hydraulic structures. *Construction and Building Materials*. Elsevier, vol. 267, p. 120966.
- Zhang, C., Xu, W., Yang, J., Cao, K., Wen, D. & Wang, X. (2022). Application of phase-field method in corrosion fracture of reinforced concrete. *Advances in Mechanical Engineering*, vol. 14(6), p. 168781322211082.
- Zhang, J., Zhang, M., Dong, B. & Ma, H. (2022). Quantitative evaluation of steel corrosion induced deterioration in rubber concrete by integrating ultrasonic testing, machine learning and mesoscale simulation. *Cement and Concrete Composites*, vol. 128, p. 104426.
- Zhang, J.-K., Yan, W. & Cui, D.-M. (2016). Concrete Condition Assessment Using Impact-Echo Method and Extreme Learning Machines. *Sensors*, vol. 16(4), p. 447.

Zhang, L., Niu, D., Wen, B. & Luo, D. (2019). Concrete Protective Layer Cracking Caused by Non-Uniform Corrosion of Reinforcements. *Materials*, vol. 12(24), p. 4245.

Zhang, W.-P., Chen, J.-P., Yu, Q.-Q. & Gu, X.-L. (2021). Corrosion evolution of steel bars in RC structures based on Markov chain modeling. *Structural Safety*, vol. 88, p. 102037.

Zhang, X. & Li, B. (2020). Damage characteristics and assessment of corroded RC beam-column joint under cyclic loading based on acoustic emission monitoring. *Engineering Structures*, vol. 205, p. 110090.

Zhao, Q., Zhou, J., Xia, Q., Zhang, S. & Zhang, H. (2019). Non-Destructive Testing of Steel Corrosion Fluctuation Parameters Based on Spontaneous Magnetic Flux Leakage and Its Relationship with Steel Bar Diameter. *Materials*, vol. 12(24), p. 4116.

Zheng, Y., Wang, S., Zhang, P., Xu, T. & Zhuo, J. (2022). Application of Nondestructive Testing Technology in Quality Evaluation of Plain Concrete and RC Structures in Bridge Engineering: A Review. *Buildings*, vol. 12(6), p. 843.