

COMMON CORROSION TYPES OF STEEL REINFORCEMENT AND MONITORING TECHNIQUES: A REVIEW

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ABSTRACT

In view of the growing requirements for sustainable design and increased service life, corrosion is regarded among the most significant issues affecting structural security, functionality and durability. Corrosion of steel reinforcements within concrete results in reduced reinforcement cross-section, loss of steel ductility, weakened bonding between the steel and concrete, and cracking of the concrete. This is the primary cause of structural degradation and failure. Therefore, this paper reviewed the corrosion mechanism, common types of corrosion that courses an essential concern of concrete structures as well as the monitoring techniques of metal surfaces.

Keywords: Corrosion, Reinforced Concrete, Monitoring, Crevice Corrosion, Steel Reinforcement.

I. INTRODUCTION

The broad availability of the components of concrete and reinforcing bars, the basic skills needed for concrete construction, and the low cost of reinforced concrete compared to other construction materials have made reinforced concrete the major engineering structural material for a wide variety of structures in many parts of the world. These structures can be guaranteed a long and efficient life, even in aggressive environments, by proper design and preparation of the concrete in accordance with ACI standards, followed by timely maintenance of the structures. Unfortunately, these steps are not universally followed [1, 2]. Consequently, civil construction projects have always met with corrosion issues affecting reinforcements, both in circumstances where the relevant standards were not observed during concrete design and preparation and in structures close to bridges, coasts, ports, quays and so on, where exposure to an aggressive environment can lead to damage such as rust spots, cracking and delamination of the concrete cover, which constitutes a hazard for the end-user. Along with the economic effects due to consequent repair costs, corrosion problems exert environmental, industrial and social impacts due to the reduced safety of the structures and to the installation of repair materials [3-6]. The published literature during the last fifty years has broadly covered the protection methodology to address this issue and the use of specially designed low-permeability concrete has been monitored since 1970 [7]. Alongside this, the major area of investigation has been the development, limitations and efficiency of electrochemical rehabilitation techniques, in particular cathodic protection systems including impressed current or sacrificial anode [8]. The use of patch repairs, coatings, sealing and membranes for concrete surface, special steel bar (stainless steel bar, epoxy coated steel reinforcement, galvanized steel reinforcing bars) and corrosion inhibitors for reinforced concrete have also been reported in the literature [9-16]. Corrosion inhibitors are regarded among the most efficient and long-term corrosion protection methodologies for steel reinforcements. Their ease of handling (as mixed-in or migrate-through components) and their low cost compared with cathodic protection make their use particularly desirable [3, 17-20]. Corrosion can be defined as the deterioration of a construction material or its properties resulting from reaction with the surrounding environment. The presence of chlorides, carbon dioxide, deicing salt, chloride-contaminated aggregates, acid attack, or a combination of these, lower the pH of the concrete, causing a breakdown of the passive film on the reinforcing steel [21]. Since the corrosion mechanism acting on reinforced concrete is an example of the general electrochemical corrosion reaction under wet conditions, three underlying factors are required for the process to occur [22]. These are:

- i. The presence of an electrolyte is essential for the transport of ions to the site of the electrochemical corrosion reaction. The concrete will always contain considerably more than enough water to act as an electrolyte.
- ii. The presence of various potentials. Differences in humidity, aeration, saline concentration, or tension in the steel can create a difference in electrical potential leading to the development of electrochemical cells.

iii. The presence of oxygen as a necessary participant in the cathodic (oxygen reduction) reaction, determining the extent to which the anodic reaction can proceed to generate the corrosion product, rust.

Corrosion cannot take place in the absence of any one of these three factors. In the presence of limited quantities of water and oxygen, corrosion will occur at a slow rate. As soon as the passive film on the steel has been compromised, iron dissolves into solution and loses electrons at the anodic site. The corrosion process takes place according to Eq. (1) and (2):



The excess electrons are used up at the cathodic site where water and oxygen are reduced to hydroxyl ions as shown in Eq. (3):



Several more oxidation stages occur leading to the formation of voluminous corrosion products (rust) which occupies a greater volume than the native steel. For example, common red rust ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$) occupies a volume slightly more than six times that of the native steel [23]. This volume increase results in an uneven distribution of expansion pressures and can generate sufficient stress to induce cracking and spalling of the surrounding concrete, the higher pressures being concentrated at the outer region of the rebar toward concrete cover [24]. Depending on the depth and spacing of the reinforcing bar, the cracks can form either immediately above the corroding bar, at right angles to the concrete surface, or at the level of the bar and parallel to the concrete surface. The oxidation reactions may be presented according to Eqs. (4) – (6) [25]:



II. COMMON CORROSION TYPES

General (Uniform) Corrosion

Among the most frequent forms of corrosion occurred in metals and alloys is that of uniform (or general) corrosion. This is the most basic form of corrosion, consisting of an even rate of metal loss over the exposed surface, usually resulting from chemical attack or dissolution of the metal constituent into metallic ions. The corrosion process is resisted by a passive surface film which forms naturally when the metal is exposed to the atmosphere for some time, or more rapidly by chemical treatment [25].

Crevice Corrosion

An especially hazardous type of localised corrosion, since it is undetectable and can lead to catastrophic failure, is crevice corrosion. This process may occur on the surface of a wide range of metal alloys due to the presence of small occluded cells under a crevice or crevices at the contact between two metals or between a metal and non-metal [26]. Crevice corrosion is notable for its variability compared to other forms of localized corrosion: onset may be immediate or delayed, and the morphology can consist of small pit-like sites or an area of attack as large as that of general corrosion [27].

Pitting Corrosion

Pitting corrosion is among the most prevalent and deceptive forms of localized corrosion. This affects passive metals in a variety of aggressive environments, the most common aggressive species being the chloride anion which is present in a wide range of natural and industrial settings. Pitting is usually concentrated on a small area of metal surface and causes structural failure by perforation or initiation of stress corrosion cracks. According to Tian et al. [28](2014), pits are initiated at the microscopic scale and are invariably covered by corrosion products, making this one of the more devastating and invisible forms of corrosion.

Atmospheric Corrosion

The main factors affecting the atmospheric corrosion of steel are time of wetness, which itself depends upon climatic factors such as temperature and relative humidity, and the presence of atmospheric constituents such as chlorides and SO_2 , which advance the process. The combination of high temperature, high humidity and high precipitation, the latter frequently leading to extended time of wetness, is typical of tropical climates [29]. Reinforcing steel bars are often exposed to the atmosphere during transportation and storage at the

construction site for extended periods of time, hence there are usually corrosion products already present on the steel surface before the bars are embedded in a concrete structure. The morphology of the rust layer formed on carbon steel is complex, being largely porous and poorly adherent, with cracks in its outer regions. These properties mean that the corrosion products do not form a barrier to the ingress of electrolyte and aggressive ions to the metal substrate, hence little protection against atmospheric corrosion is afforded [30].

Stray Currents Corrosion

Corrosion of buried metal structures, resulting in extreme localised attack, is often the result of stray currents from railways, cathodic protection systems, or high voltage power lines for example [31]. The current will depart from its intended path if an alternative and parallel route is available, and a low resistance route may be found that takes the current through buried reinforced or prestressed concrete structures. This will produce an alteration in the electrical field inside the concrete, which can affect corrosion of the embedded steel. A range of structures, including railway bridges and tunnels, or other structures located in the vicinity of railways, can be affected by stray currents [32]. Figure 1 shows how the reinforcing bars or prestressing wires can pick up the stray current from a railway system at some location far from the traction power substation, discharge the current to the concrete which acts as the electrolyte, and then return the current to the rail close to the substation. Depending upon the source, the stray currents can be alternating (AC) or direct (DC). Stray DC currents are considerably more hazardous than AC, the former inducing a cathodic reaction (oxygen reduction or hydrogen evolution) at the point of entry into the buried structure and an anodic reaction (metal dissolution) at the point of exit. Thus, metal loss takes place at the anodic site, where the current leaves the structure, leading to a highly localized form of corrosion which can have serious effects, particularly upon steel reinforcements in concrete [33].

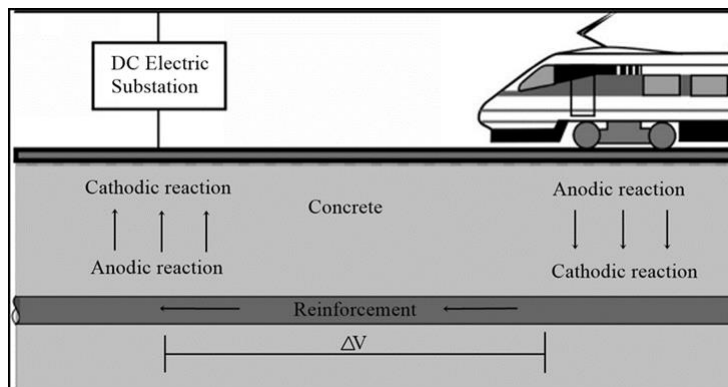


Figure 1: Stray current from a dc railway line picked up by rebar in concrete [34].

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is among the major causes of breakdown in prestressed concrete structures, being responsible for 20 – 30% of steel damage in the chemical industry, for example. Prestressed concrete structures are generally made of high-performance concrete and high-strength steel loaded at very high levels of tension. On a global scale, the strategic significance of infra-structures such as road bridges, rail bridges, power plants, and so on, make deteriorating prestressed concrete structures one of the most problematic classes of construction materials. Stress corrosion is more acute than other forms of corrosion, since it leads to sudden, brittle failure of tendons without any perceptible warning signs and without detectable ultimate elongation [35]. In tandem with stress corrosion cracking, embrittlement may occur due to penetration of the steel by hydrogen gas produced during the corrosion reaction. Three factors are essential to the initiation of stress corrosion, namely: susceptibility of the variety of steel used, the application of stress beyond a minimum threshold value below which the process is imperceptibly slow, and the presence of a specific aggressive medium (which may or may not generate hydrogen gas) [36]. When the above three factors operate together the process of stress corrosion advances in three stages, beginning with the initiation of one or more micro-cracks at the steel surface, continuing with gradual growth of the cracks until they reach a specific depth, after which they propagate extremely rapidly. The process concludes with brittle failure of the steel, which may be encouraged by hydrogen embrittlement. The loss of metal during the first stage is negligible and the corrosion potential measured at the concrete surface may not indicate the onset of the process. Hence the initial stages of

corrosion cannot be detected by corrosion rate measurement and traditional electrochemical techniques can only be used to assess the risk of occurrence. SCC is generally favoured by the presence of sulphides, sulphates or thiocyanides, whereas chlorides are less commonly involved in this kind of degradation [36].

Galvanic Corrosion

Also among the most frequent forms of corrosion affecting engineering structures in everyday use is galvanic corrosion. This was originally defined as the augmented corrosion at the contact between two or more dissimilar metals. As described by Yin et al. [37], the joining together of two different metals or alloys, either directly or via an external pathway, enhances the corrosion rate of the anodic alloy (that possessing the more negative potential) while decreasing or restraining the corrosion rate of the cathodic alloy (that possessing the more positive potential). The process is affected by a range of factors including the electrode potential of the different metals, the area of contact of the metals, the area of each metal exposed to an electrolyte, the properties of the electrolyte, the temperature of the electrochemical solution, and so on [37, 38].

Intergranular Corrosion

One of the most significant localized corrosion issues for stainless steel components in high temperature-high pressure environments is intergranular corrosion (IGC). This is defined as selective corrosion at grain boundaries or close neighbouring regions without significant attack taking place within the body of the grains or crystals. In this process the grain boundaries become anodic, while the bulk material in between is unaffected and hence becomes cathodic. The properties of IGC render it a frequently fast and deeply penetrating attack which can lead to sudden failure due to diminished binding force between the crystal grains and a compromise in the mechanical strength of the affected material [39].

Corrosion Fatigue

Tension reinforcements for concrete are usually made of high strength low alloy steel, and fatigue failure of RC structures is largely down to failure of these. The location of the failure corresponds to the presence of tension cracks within the concrete, which cause the full intensity of the strain to be concentrated onto the steel reinforcement. In the presence of a corrosive environment, the cracks within the concrete afford the corrosive medium comparatively free access to the highly strained area of the steel, leading to the process of corrosion fatigue [40]. This mechanism is potentially harmful to the service lifetimes of structures subjected to chloride-containing solutions, such as highway structures, structures near marine coastlines, and offshore structures. The three stages involved in the fatigue mechanism are: (i) initial crack formation, (ii) crack growth and progressing across part of the reinforced concrete, and (iii) ultimate acute failure of the remaining cross-section [41].

III. CORROSION MONITORING TECHNIQUES

A large number of important reinforced concrete structures have begun to show signs of distress within a short time. The condition of these structures is generally monitored by visual inspection and hence remedial action is taken only when heavy rusting of the steel reinforcements has resulted in visible cracking and spalling of the concrete, at which time the situation has become very serious. It would be preferable to be able to monitor the condition of such important structures by means of regular corrosion assessments and keeping a record of data all the way through from the construction stage. Song and Saraswathy [42] have recommended the use of several available electrochemical and non-destructive techniques or measuring the corrosion rate of steel reinforcements in concrete structures. A wide variety of techniques including measurement of open circuit potential (OCP), surface potential (SP), concrete resistivity and linear polarisation resistance (LPR), as well as Tafel extrapolation, the galvanostatic pulse transient method, electrochemical impedance spectroscopy (EIS), harmonic analysis, noise analysis, embeddable corrosion monitoring sensor, cover thickness measurements, the ultrasonic pulse velocity technique, X-ray, gamma radiography, infrared thermography, electrochemical and visual inspection can all be applied to the assessment of rebar corrosion on existing structures. Integrated monitoring systems and procedures have a significant role to play. The development of integrated monitoring systems for new and existing reinforced concrete structures could reduce costs by allowing a more rational approach to the assessment of concrete structures. The development of corrosion monitoring systems for new and existing reinforced concrete structures arose from the emergence of durable, embeddable sensors along with economical microprocessor control and communications. The resulting possibility for real-time

continuous monitoring of the steel reinforcements and concrete cover could make more information available regarding the present and future performance of the structure. Corrosion monitoring could therefore become a central aspect of planned maintenance and service life prediction, providing quantitative data regarding the progression of corrosion as aggressive conditions build up in the concrete following chloride ingress or carbonation. It can also be used to evaluate the effectiveness of rehabilitation measures such as coatings or corrosion inhibitors. With this in mind, installations have been applied to new structures having long life requirements for planned maintenance and to prevent premature repair requirements. Sensors are also being used as part of a rehabilitation strategy for structures showing signs of corrosion, making it possible to evaluate the outcome of repairs and to determine the future maintenance cycle. Monitoring systems can incorporate sensors for measuring both the corrosion rate and the concrete condition. The deployment of sensor systems to assess the performance of steel reinforcements and concrete cover is therefore an important component of an integrated monitoring system.

IV. CONCLUSION

An analysis to the published literature demonstrates a general agreement that one of the most significant problems affecting reinforced concrete structures is corrosion of the steel reinforcements. The formation of an oxide layer on the surface of the steel rebar, with consequent reduction in cross-sectional area, strength, and ultimately the security of the overall structure, makes this process one of significant research interest. This paper is aimed to broadly review the main types of corrosion that affected the steel reinforcement in concrete. Pitting corrosion in addition to general and localized corrosion is regarded as the most hazardous corrosion of reinforced concrete. Open circuit potential (OCP), surface potential (SP), concrete resistivity, linear polarization resistance (LPR), as well as Tafel extrapolation, the galvanostatic pulse transient method, electrochemical impedance spectroscopy (EIS) are the most techniques used to detect the corrosion rates of metals.

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V. REFERENCES

- [1] J Hackl, J. Kohler, Reliability assessment of deteriorating reinforced concrete structures by representing the coupled effect of corrosion initiation and progression by Bayesian networks, *Structural Safety* 62 (2016) 12-23.
- [2] M.A. Asaad, M. Ismail, M.M. Tahir, G.F. Huseien, P.B. Raja, Y.P. Asmara, Enhanced corrosion resistance of reinforced concrete: Role of emerging eco-friendly Elaeis guineensis/silver nanoparticles inhibitor, *Construction and Building Materials* 188 (2018) 555-568.
- [3] F.-l. Fei, J. Hu, J.-x. Wei, Q.-j. Yu, Z.-s. Chen, Corrosion performance of steel reinforcement in simulated concrete pore solutions in the presence of imidazoline quaternary ammonium salt corrosion inhibitor, *Construction and Building Materials* 70 (2014) 43-53.
- [4] W. Slika, G. Saad, An Ensemble Kalman Filter approach for service life prediction of reinforced concrete structures subject to chloride-induced corrosion, *Construction and Building Materials* 115 (2016) 132-142.
- [5] E.A. Liberati, C.G. Nogueira, E.D. Leonel, A. Chateauneuf, Nonlinear formulation based on FEM, Mazars damage criterion and Fick's law applied to failure assessment of reinforced concrete structures subjected to chloride ingress and reinforcements corrosion, *Engineering Failure Analysis* 46 (2014) 247-268.
- [6] Roman Fediuk, Valery Lesovik, M.A. Asaad, Effect of polymineral systems and disperse reinforcement on self-compacting fibre concrete, *Magazine of Concrete Research* 1900447 (2021) 1-17.
- [7] M.I. Khan, C. Lynsdale, Strength, permeability, and carbonation of high-performance concrete, *Cement and Concrete Research* 32(1) (2002) 123-131.
- [8] G. Glass, A. Hassanein, N. Buenfeld, Cathodic protection afforded by an intermittent current applied to reinforced concrete, *Corrosion Science* 43(6) (2001) 1111-1131.
- [9] A.S. Abdulrahman, M. Ismail, Evaluation of corrosion inhibiting admixtures for steel reinforcement in concrete, *International Journal of the Physical Sciences* 7(1) (2012) 139-143.

- [10] M.A. Asaad, N.N. Sarbini, A. Sulaiman, M. Ismail, G.F. Huseien, Z. Abdul Majid, P. Bothi Raja, Improved corrosion resistance of mild steel against acid activation: Impact of novel *Elaeis guineensis* and silver nanoparticles, *Journal of Industrial and Engineering Chemistry* 63 (2018) 139-148.
- [11] M.A. Asaad, M. Ismail, P.B. Raja, N.H.A. Khalid, *Rhizophora apiculata* as eco-friendly inhibitor against mild steel corrosion in 1 M HCl, *Surface Review and Letters* 24(8) (2017) 1-11.
- [12] M.A. Asaad, M. Ismail, G.F. Huseien, P.B. Raja, *Elaeis guineensis* leaves extracts as eco-friendly corrosion inhibitor for mild steel in hydrochloric acid, *Jurnal Teknologi* 80(6) (2018) 53-59.
- [13] E. Cadoni, L. Fenu, D. Forni, Strain rate behaviour in tension of austenitic stainless steel used for reinforcing bars, *Construction and Building Materials* 35 (2012) 399-407.
- [14] J.A. Calderón, J.E. Henao, M.A. Gómez, Erosion–corrosion resistance of Ni composite coatings with embedded SiC nanoparticles, *Electrochimica Acta* 124 (2014) 190-198.
- [15] F. Tittarelli, G. Moriconi, The effect of silane-based hydrophobic admixture on corrosion of galvanized reinforcing steel in concrete, *Corrosion Science* 52(9) (2010) 2958-2963.
- [16] G.F. Huseien, M. Ismail, M.M. Tahir, J. Mirza, N.H.A. Khalid, M.A. Asaad, A.A. Husein, N.N. Sarbini, Synergism between palm oil fuel ash and slag: Production of environmental-friendly alkali activated mortars with enhanced properties, *Construction and Building Materials* 170 (2018) 235-244.
- [17] M.A. Asaad, Commercial and Green Corrosion Inhibitors for Reinforced Concrete Structures: A Review, *International Journal of Current Science Research and Review* 04(02) (2021).
- [18] M.A. Asaad, M.N. Hussein, A.T. Saleh, Corrosion inhibitors for reinforced concrete structures exposed to aggressive environments: a review, *International Research Journal of Modernization in Engineering Technology and Science* 03(02) (2021) 19-27.
- [19] G.F. Huseien, M.M. Tahir, J. Mirza, M. Ismail, K.W. Shah, M.A. Asaad, Effects of POFA replaced with FA on durability properties of GBFS included alkali activated mortars, *Construction and Building Materials* 175 (2018) 174-186.
- [20] G.F. Huseien, A.R.M. Sam, J. Mirza, M.M. Tahir, M.A. Asaad, M. Ismail, K.W. Shah, Waste ceramic powder incorporated alkali activated mortars exposed to elevated Temperatures: Performance evaluation, *Construction and Building Materials* 187 (2018) 307-317.
- [21] L. Abosrra, A.F. Ashour, M. Youseffi, Corrosion of steel reinforcement in concrete of different compressive strengths, *Construction and Building Materials* 25(10) (2011) 3915-3925.
- [22] J.B.d. Souza, E.P.d. Deus, Damage Mechanics Applied for Steel Reinforcements in Concrete Structures under Corrosion, *Procedia Materials Science* 3 (2014) 2000-2005.
- [23] L. Abosrra, A. Ashour, M. Youseffi, Corrosion of steel reinforcement in concrete of different compressive strengths, *Construction and Building Materials* 25(10) (2011) 3915-3925.
- [24] X. Du, L. Jin, R. Zhang, Modeling the cracking of cover concrete due to non-uniform corrosion of reinforcement, *Corrosion Science* 89 (2014) 189-202.
- [25] P.A. Schweitzer, *Fundamentals of corrosion: mechanisms, causes, and preventative methods*, CRC Press 2009.
- [26] W. Sun, L. Wang, T. Wu, G. Liu, An arbitrary Lagrangian–Eulerian model for modelling the time-dependent evolution of crevice corrosion, *Corrosion Science* 78 (2014) 233-243.
- [27] Y.Z. Yang, Y.M. Jiang, J. Li, In situ investigation of crevice corrosion on UNS S32101 duplex stainless steel in sodium chloride solution, *Corrosion Science* 76 (2013) 163-169.
- [28] W. Tian, N. Du, S. Li, S. Chen, Q. Wu, Metastable pitting corrosion of 304 stainless steel in 3.5% NaCl solution, *Corrosion Science* 85 (2014) 372-379.
- [29] J.G. Castaño, C.A. Botero, A.H. Restrepo, E.A. Agudelo, E. Correa, F. Echeverría, Atmospheric corrosion of carbon steel in Colombia, *Corrosion Science* 52(1) (2010) 216-223.
- [30] E. Zitrou, J. Nikolaou, P. Tsakiridis, G. Papadimitriou, Atmospheric corrosion of steel reinforcing bars produced by various manufacturing processes, *Construction and Building Materials* 21(6) (2007) 1161-1169.

- [31] L. Sandrolini, Analysis of the insulation resistances of a high-speed rail transit system viaduct for the assessment of stray current interference. Part 2: Modelling, *Electric Power Systems Research* 103 (2013) 248-254.
- [32] L. Bertolini, M. Carsana, P. Pedferri, Corrosion behaviour of steel in concrete in the presence of stray current, *Corrosion Science* 49(3) (2007) 1056-1068.
- [33] M. Raupach, B. Elsener, R. Polder, J. Mietz, *Corrosion of Reinforcement in Concrete: Monitoring, Prevention and Rehabilitation Techniques*, Woodhead Publishing 2014.
- [34] A.O.S. Solgaard, M. Carsana, M.R. Geiker, A. Küter, L. Bertolini, Experimental observations of stray current effects on steel fibres embedded in mortar, *Corrosion Science* 74 (2013) 1-12.
- [35] A. Torres-Islas, J.G. Gonzalez-Rodriguez, J. Uruchurtu, S. Serna, Stress corrosion cracking study of microalloyed pipeline steels in dilute NaHCO₃ solutions, *Corrosion Science* 50(10) (2008) 2831-2839.
- [36] V. Raja, T. Shoji, *Stress corrosion cracking: theory and practice*, Elsevier 2011.
- [37] Z.F. Yin, M.L. Yan, Z.Q. Bai, W.Z. Zhao, W.J. Zhou, Galvanic corrosion associated with SM 80SS steel and Ni-based alloy G3 couples in NaCl solution, *Electrochimica Acta* 53(22) (2008) 6285-6292.
- [38] A. Ravi Sankar, S. Das, Experimental analysis of galvanic corrosion of a thin metal film in a multilayer stack for MEMS application, *Materials Science in Semiconductor Processing* 16(2) (2013) 449-453.
- [39] D. di Caprio, J. Stafiej, G. Luciano, L. Arurault, 3D cellular automata simulations of intra and intergranular corrosion, *Corrosion Science* 112 (2016) 438-450.
- [40] Y.J. Kim, P.J. Heffernan, Fatigue behavior of externally strengthened concrete beams with fiber-reinforced polymers: state of the art, *Journal of Composites for Construction* 12(3) (2008) 246-256.
- [41] M.A. Maleque, M.S. Salit, *Materials selection and design*, Springer 2013.
- [42] H.-W. Song, V. Saraswathy, Corrosion monitoring of reinforced concrete structures - A Review, *International Journal of Electrochemical Science* 2 (2007) 1-28.