CORROSION PROBLEMS IN RC STRUCTURES: AN OVERVIEW OF CAUSES, MECHANISM, EFFECTS, CONTROLS AND EVALUATION

Kabir Sadeghi[1], Muhammad Khidre Musa[2], Hazar M. Nassrullah[3]

[1]Professor, Civil Engineering Department, Near East University, North Cyprus, Nicosia;
[2]Research Scholar, Civil Engineering Department, Near East University, North Cyprus, Nicosia;
[3]Researcher, Civil Engineering Department, Near East University, North Cyprus, Nicosia, TURKEY.

[1]kabir.sadeghi@neu.edu.tr, [2]mmkidre @gmail.com, [3]hazhareng83@yahoo.com

ABSTRACT

The Goal of this research is to survey the corrosion problem in the steel of reinforced concrete structures. The reason for corrosion and technique of prevention of corrosion of reinforcing bars is investigated. When reinforcement corrodes, the creation of rust separates the concrete form the steel and subsequently. If this problem is not treated the whole structure will be affected.

Keywords: Corrosion, reinforced concrete structure, carbonation, chloride, sulfate

INTRODUCTION

Corrosion is described as damaging of materials due to subjecting to different environmental action, sole, or when combination with other factors. For metallic substance, rust and corroding commonly include oxidization and is thus an electrochemical event. (Gonçalves and Margarido. 2015).

The steel in reinforced concrete (RC) structures are preserved in inactive state by a thin film of oxide which is because of concrete alkalinity (PH between 12 to 13), unluckily, owing to the decadence of concrete this highly favorable value is not often sustained during the service time of concrete, which causes corrosion of the reinforcement (Ormellese et al., 2006).

The steel bars in RC structures are exposed to general deterioration among various degradation mechanisms.

Reinforcement corrosion is the major factors of the detrimental and primary defeat of RC structures around the world with succeeding high cost for repair, recovery, and substitution. Corrosion phenomenon is generally quicker as compared to other kinds of degradation, particularly in the regions with atmosphere pollution produced by industrial exhaust smoke chimney, etc., and the zone near to littoral boards. The main and earnest factor that causes of low durability of concrete is the corrosion concern. The process of corrosion starts by the entrance of humidity, oxygen and other detrimental materials into the concrete microstructures, which is permeable, absorbent and unsound. The humidity and extra adverse components also entered to the concrete via cracks owing to structural and other types of cracks (Kashaniea al., 2016).

CORROSION AND SERVICE LIFE LOAD OF RC STRUCTURES

Concrete deterioration is a chief responsibility for the building industry as the expenditure to maintenance and damaged structure can't reach to its design life without major maintenance. Billions of dollars in America are consumed each year for the purpose of maintaining the damaging RC structures. A project free from any corrosion can increase the age of the project for more than 100 years in the absence of any chief preservation and repairing expenditure.

ISSN: 2223-9944, e ISSN: 2223-9553
www.journals.savap.org.pk

This reality obviously represents the importance of fiberglass rebars in the construction of structures that are resistant to corrosion.

EFFECT OF CORROSION IN RESISTANCE AGAINST EARTHQUAKE

In the last few decades, rusting of steel rebar is identified among the chief reasons contributing to the insufficient seismic proficiency of available RC structures. Oxygen influences, chloride ions, carbonations, inadequate cover, etc. may lead to corrosion in of RC structures. Anticipate deterioration in the existing RC structures owing to reinforcement corrosion is initially rely on the reason levels of corrosion proportion, corrosion quantity, corrosion situation and, destruction in cross-sectional area of rebars**.**

Corrosion is an event dependency on time, combined with various criteria such as the quantity of corrosion, beginning time of corrosion, the proportion of corrosion, etc. (Turkish Seismic Design Code, 2007). The TSDC (2007) suggested that during the design of the structure, reinforcement corrosion should be appraised in. (Yet al., 2012).

Ma, Che and Gong (2012) supervise test research of seismic execution damaging of 13 RC columns under unifying cyclic lateral movement circulation and steady axial load since it is exposed to speed up corroding experiment. The control changeable was the steel corrosion deficit proportion varying between 0% to 15.1% and the axial load proportion ranging from 0.15 to 0.9. High level of corrosion proved coupled with high axial load lead to decrease stability hysteretic curlicues with a large decrease in strength and stiffness and bad ductility (Ou and Nguyen, 2016).

Corrosion problems result in reduced ductility, structural capacity, and decrease stiffness. Corrosion significantly affects and endangered structural building. Depending on the results of some research, the consequences of corrosion may result in a rise in the chances of structural failure in 50 years of service to up to 4 times (Quraishi et al., 2017).

CLASSIFICATION OF CORROSION

Different kinds of corrosion can affect the metal in a diversity of methods, which rely on its character and the accurate environmental status predominant, and a wide classification of the various forms of corrosion, in which five main categories have been recognized, is shown in Table 1, (Quraishi et al.,2011)

Table 1. Corrosion Types (Quraishi et al., 2011)

Types of corrosion	Characteristic	Examples
1. Selective dissolution	One of the most active components of a mixture is the chosen eliminate from an alloy	Dezincification; stratification; graphitization
2. Pitting	particularly localized attack at special region eventuate in small cavity that creating into the metal and may lead to a hole	make holes in one of the inactive metals such as the aluminum alloys, stainless steels, etc., in the availability of special ions, for example, Clions
3. Localized	Higher rate of corrosion on some specific region of the metal surface owing to 'dissimilarities' in the environment, metal, the or in the microstructure as a whole.	split corrosion; thread corrosion; sediment attack; bimetal corrosion; intergranular corrosion; weld damage

ISSN: 2223-9944, e ISSN: 2223-9553
www.journals.savap.org.pk

	Attack can range from being little localized to creating holes	
4. Uniform (or almost uniform)	All part of metal corroded at the same proportional	blemish and Oxidation; anodic oxidation and passivity; active dissolution in acids; chemical and plunge corrosion in special state electrochemical polishing; atmospheric
5. Conjoint action of corrosion and a mechanical factor	situated attack or break owing to the cooperative function of a corrosion factor and corrosion mechanical	corrosion – Erosion, scowl corrosion, impaction attack, hydrogen cracking, cavitation's damage; stress corrosion cracking, corrosion fatigue

CORROSION MECHANISM IN CONCRETE

Corrosion in concrete is persuaded by producing electrochemical potentials itemized in the methods given below:

1. Presence of metals with different potentials within the RC structure such as aluminum pipe, steel rebar, or when considerable alteration exist on the surface properties of the steel results in the creation of compound cell that may influence the corrosion (Mehta and Monteiro, 2006).

2. Condensation cells may be produced near reinforcing steel due to the diversity in the aggregation of solvable ions, similar to chlorides and alkalis (see Figure 1), (Neville, 2005).

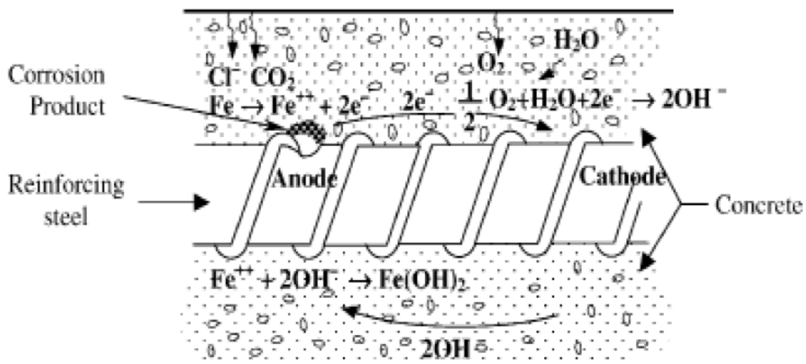

Figure 1. Corrosion system of steel in concrete (Neville, 2005)

Some criteria are necessary to start corrosion. Availability of oxygen, humidity (electrolyte) are the two important criteria without which corrosion is not possible. Limited supply and non-presence of humidity and oxygen at the rebar level limits the corrosion rate. The water, oxygen and high relative humidity serve as a catalyst that facilitates occurrence and acceleration of corrosion by supplying more hydroxyl ions thus producing ferric hydroxide known as the rust.

CORROSION EVALUATION

Corrosion detector or monitor is the practice of continuously assessing the corrosion process in a structure exposed to the deleterious environment by utilizing of "probes" which are placed into the process stream and which are frequently subjected to the process flow condition. The popular methods utilized for estimation of corrosion can be summarized as follows:

Corrosion Coupons

Corrosion Coupons for indicating corrosion is noncomplex and the oldest method of evaluation of corrosion detect in plant and is advised by the analysis of weight detriment of the coupons (Tehada and Hernandez, 2013).

Electrical Resistance (ER)

This technique is the most broadly employed technique for estimating material loss happening inside the device and pipefitting. This method practice by evaluating the alteration in the persistence of metallic components for electrical resistance plunged in a yield media relative to recourse components enfolded in the probe frame. (Brown et al., 2014).

Linear Polarization Resistance (LPR)

Persistence for Polarization has significantly utilized a technique to quickly determine corrosion disturbance and beginning recovery function, therefore extending device life and reducing nonprogrammatic downtime. (Brown et al., 2014).

Inductive Resistance (IR) Probes

IR probes have more similarity to the ER but offer particularly ameliorate sensibility. Variation of mass in the recorder component is detected by calculating changes in the analogical coil insistence, situated instant the device. For a given indicator component life, these probes will try to show a variation in corrosion amount much in the near future than the equivalent ER issue. (Grossi and Riccò, 2016).

Electrochemical Impedance Spectroscopy (EIS)

EIS has extensively been used to investigate corrosion problem for long and it found to be a strong and reliable technique for evaluating the rate of corrosion. But to accessibility the charge transmission persistence or resistance to the polarity that is proportionate to the amount of corrosion at the observed junction, EIS consequently has to be clarified using the interface model. Hz (Obot and Onyeachu, 2017).

Electrochemical frequency modulation

This is also an electrochemical method where two like-sine function potential signals are summarized and used to sample corrosion via a potentiostat. The resulting running estimates and the time-domain data is altered to the periodicity area of expertise to evaluate the signal at the practical basement frequencies, at a pitch of the basement frequencies, and at intermodulation frequencies (Vedalakshmi et al., 2009).

Harmonic Analysis for Corrosion Monitoring

Faster and more direct corrosion rate results can be achieved using this new technique as it only requires a small frequency range. Harmonic analysis is conducted by sending A.C. voltage at an alone frequency and recording the corresponding A.C. current density, and at the same time recording two higher harmonics. (Rivera and Castaño, 2012).

Electrochemical Noise (EN)

EN is a non-obstructive technique for corrosion evaluation that is so marvelous for example airplane corrosion and gas erosion tower monitoring examples. Oscillation of potential or running of a metallic corrosion sample are a commendable and simply perceivable event and the estimation of EN as a corrosion device has progressed steadily. (Nayak, 2013).

Zero Resistance Ammetery (ZRA)

This electrochemical technique is reached using a potentiostat. A potentiostat is an electronic tool which regulates the voltage difference between the reference electrode and test electrode. The electrodes are both within the electrochemical cell. The potentiostat regulates the voltage by instilling current into the cell through a secondary electrode. (Enos and Scribner1997).

Potentiodynamic polarization methods

Polarity techniques such as potentiostaircase, polarization, potentiodynamic, potentiostaircase, and recurrent voltammetry are generally employed for corrosion experiment in the laboratory. These methods can supply considerable benefit data about the corrosion procedure, corrosion proportional and susceptibleness of special materials to corrosion in designated environments (Biswas et al., 2016).

Thin Layer Activation (TLA)

In this corrosion indicating technique progressed from the site of atomic knowledge, a small part of the sample is subjected to a huge ray beam of charged particles, to build a radioactive layer on the shell. The radioactive effects used are at extremely low phase and quantity and cannot be contrasted to those of regular radiography (Kawakam et al., 2011).

Electrical Field Signature Method (FSM)

The basic progress of this method was highly diverted at oil and gas production. This corrosion indicating method evaluate corrosion defective over some meters of a factual structure and supply evaluation of metal defective over a pipefitting surface. (Zhou, 2011)

Acoustic Emission (AE)

Corrosion monitoring with AE is a function on evaluating acoustic sound waves produced due to microscopic damage, like the cracks that occur as a result of stress corrosion. (Kuang et al., 2010)

Corrosion Potential (E_{corr}) Monitoring

The evaluation of the potential corrosion, usually called E_{corr}, is a relatively easy implication, with the fundamental standard largely employed in industry for indicating steel corrosion in concrete like a conceal pipelines subject cathodic conservation. Monitoring the anodic preservation technique is a more relevant area. (Eun, 2004).

Hydrogen Flux Monitoring

Atomic hydrogen is one of the popular corrosion generations of iron or steel in a neutral or acidic medium. Commonly, these extremely reactive categories incorporate with other hydrogen atoms to create a relatively innocuous molecule, hydrogen gas (H_2). In the availability of some catalysts such as tin, arsenic, sulfur, the hydrogen atoms solved into the steel to a considerable rate. (Wilmot, 2007)

Chemical Analyses

Various kinds of chemical analyses can supply worth data in corroding controlling system. The evaluation of PH, conduction, solvable metallic, oxygen, and another ion condensation, the alkalinity of watery, aggregation of hanging particles, prohibition concentrations, and scaling shows the whole drop within this area. Some of these mensurations lead to building on-line applying suitable sensors.

ISSN: 2223-9944, e ISSN: 2223-9553

CORROSION CONTROL AND PREVENTION

Quality of Concrete

The active evaluation refers to the recovery of the durability of concrete that includes the use of high quality concretes produced by the incorporation of various chemical admixtures (e.g.: superplasticizers, plasticizers, admixture, shrinkage reducing, admixture, mineral admixtures, and corrosion inhibitors).

Use of superplasticizers

Superplasticizer reduces water content in the high range. Superplasticizers can reduce the needed water until 30 percent without affecting workability. In briefly it highlights the importance of superplasticizers and presented the properties of concretes in terms of permeability progressing of strength, pore structure, microstructure and carbonation (Dinakar et al., 2007)

Provision of adequate concrete cover

The depth concrete cover is the major factor that significantly prevents steel corrosion embedded in reinforcement. Feasible perspective envisages during building could agreement final depth of covers. 24 mm considerable concrete cover estimated 100 years to starting of reinforcement corrosion (Zongjin, 2011).

Use of pozzolans and Admixtures

Admixture similar as rice husk, fly ash, air-entraining admixture, slag met kaolin, alccofine, etc. may be utilized as parochial substitution with ordinary cement (OPC) to ameliorate the properties of concrete and extra decrease the utilization of crude substance. Pozzolanic reactions are primary slow; hence the heat of hydration and strength progression will also be slow. The passivity of steel in RC is reduced due to the reduction in coliseums hydroxide because of pozzolanic reaction and at the same time the additional secondary cementitious material is created which fills the voids of concrete making it dense and therefore gives more persistence to the corrosion of reinforcement. (Broomfield, 1995)

Corrosion prevention

Inhibitors corrosion can be classified in tow main kinds. The first kind is named the anodic inhibitor. The second kind is the cathodic inhibitor. The first one relay on an inactive conservation film on a steel bar in concrete.

Anodic Inhibitors

Calcium nitrate is the most commonly used anodic inhibitor. It is appropriate with streaming concrete at the site where there is no harmful effect on the qualities of concrete if it is in hardening or fresh condition. Sodium and potassium nitrate are also used for anodic inhibition due to their high efficiency in corrosion forbiddance, but cannot be used where there are aggregates alkaline since sodium and potassium seems to react with cement and lead to immense degradations to the concrete. (Yu et al., 2015).

Cathodic Inhibitor

Cathodic prevention is included in the concrete mix at the time of the mixture. Alternative sort of cathodic inhibition requires painting surface of hardened concrete and move the steel bars via the concrete’s porosity, therefore, limiting the amount of oxygen that diffuses through the concrete. Presence of oxygen at the rebar level is the important cause of the corrosion actions.

ISSN: 2223-9944, e ISSN: 2223-9553
www.journals.savap.org.pk

Covering of the rebar by Epoxy

Coating the rebars with epoxies capable of protecting the rebar against corrosion is very essential. The method proved to be very effective especially where the structures are in proximity to seawater. Studies conducted by the federal highways association (FHWA) to appraise the effectiveness of the epoxy in coating the steel against the ingress of chloride attack shows a remarkable performance.

ASTM A 775M/77M-93 provides the following conditions for the effective performance of the epoxy coating:

- No more than 6 pinholes should be provided per 1m length.
- The range of 130–300 microns
- The degradation area on the bar must not exceed 2%.

Galvanized Steel Bars

Several studies in America recommends galvanizing the reinforcement in an RC structural member. Subsequent to bending of the reinforcement the steel is testing the galvanized coating. The highest thickness of zinc coating is nearly 200 microns according to the American Society for Testing and Materials-90. Laboratory experimental have used various kinds of ordinary cement with diverse alkalinity. (Überblick, and Aperçu, 2005).

Stainless Steel

Stainless steel has proven to be effective alternative rebar in preventing corrosion in RC structures but with additional cost. Since stainless steel cost a bit higher than ordinary steels, ordinary steels are therefore coated with stainless steel of 1 to 2 mm thickness are used to obtain the same function. Stainless steel should not be used together with non-stainless or uncoated stainless as that may result in rapid corrosion in the non-stainless rebar. (Prachasaree et al., 2015).

Fiber Reinforcement Bars

The use of fiber rebars has been practically and theoretically proven to be a good alternative in RC structures in the last few decades as these rebars do not corrode and are also economical in the long term. The fiber reinforced rebars are much lighter than the steel having a density of $2.5 g/cm^3$ that is about one-third that of the steel bars. It can be used to add the floor in the renovation of an existing structure and also used to substitute steel handrails, grating, and ladders in offshore structures. (Bashi et al., 2003).

Cathodic Protection by Surface Painting

Carbonation and ingress of chloride ions were believed to be major factors considered to be breaking the passive layer protecting rebars in RC components by lowering the alkalinity of the reinforced structures in the presence of water and oxygen to cause corrosion.

Cathodic Protection System

The cathodic protection system is very costly that is why it is mostly used in the oil sector for protecting oil pipelines against corrosion. The method is applied only on some specific and very important RC structures due to the high cost in execution, designing, and monitoring. If properly applied, the method completely prevents the rebars against corrosion and also has the ability to stop corrosion in places where it is already on. (Du et al., 2005a).

ISSN: 2223-9944, e ISSN: 2223-9553

THE EFFECTS OF CORROSION ON RC STATURES

Corrosion of rebar in RC is very problematics as it destroys both the rebar and the concrete itself. The diameter of the corroded bars is less than the actual steel diameter making it difficult to support the loads to carry (Du et al., 2005a, 2005b). In the corroded section of the steel, rust accumulates at the cathode zone of the steel causing expansion which will yield cracks that will make the structure to start breaking. (Lundgren, 2005).

Mechanical properties of corroded steel bars

Generally, corrosion can be grouped into local and general corrosion. Corrosion that appears uniform across the length of the steel bars is termed general corrosion while the corrosion that formed on a particular spot causing pits is called localized corrosion. Carbonation results in generalized corrosion while chloride attacks cause localized corrosion. (CEB-fib, 2000).

Localized corrosion results in a decrease in the strain of the steel reinforcement. It is enough with only ten percent of inhomogeneous corroding to decrease the ductility of bars entrenched in the reinforced structures to under the least possible necessity describes in the code of design, codes for utilization in large ductility conditions. Besides, stress-strain properties of the rusted bar in concrete demonstrate reduce in the ductility with an increment in the corrosion rate. Other steel criteria, similar to yielding and terminal stresses, are considerably diminished due to rusting. (Du., 2005a).

Connection and bonding between rusting steel bar and concrete

According to experimental tests, decrement in the strength of steel bar for bonding by increment the rate of corrosion. The bond strength of the lower bars layer is about 25% higher than top bars for the sample without any corrosion and about 30% for bars with rough corrosion. Nevertheless, on the occasion of temperate corrosion, there is no considerable discrepancy of bond strength between lower and top layer bars. The increment of the concrete cover e from 20 to 50 mm eventuated in a betterment of the bond strength. However, the difference of bond strength between both cover was less distinct for the intensive corrosion rate. (Sonebi et al., 2011).

Decreasing of Strength

The cross-sectional of the structural constituent is decrement by corrosion. A diminution in the rebar diameter decreases the flexural and axial strength of components, and cause brittle of structural.

Fatigue

Corrosion leads to the decrement of the fatigue capability of steel constituent, connections, and reinforced structural components. Corrosion increases the rate of dissemination fatigue crack in structural steels (Apostolopoulos and Pasialis, 2010).

Limited Ductility

The ductility of RC sections reduces in high range by the corrosion. This is dangerous in earthquake design and evaluation. The plastic deformation is finite in lower ductility, and this will have a negative influence on the seismic response of the elements. Asri and Ou (2011). See Figure 2.

ISSN: 2223-9944, e ISSN: 2223-9553

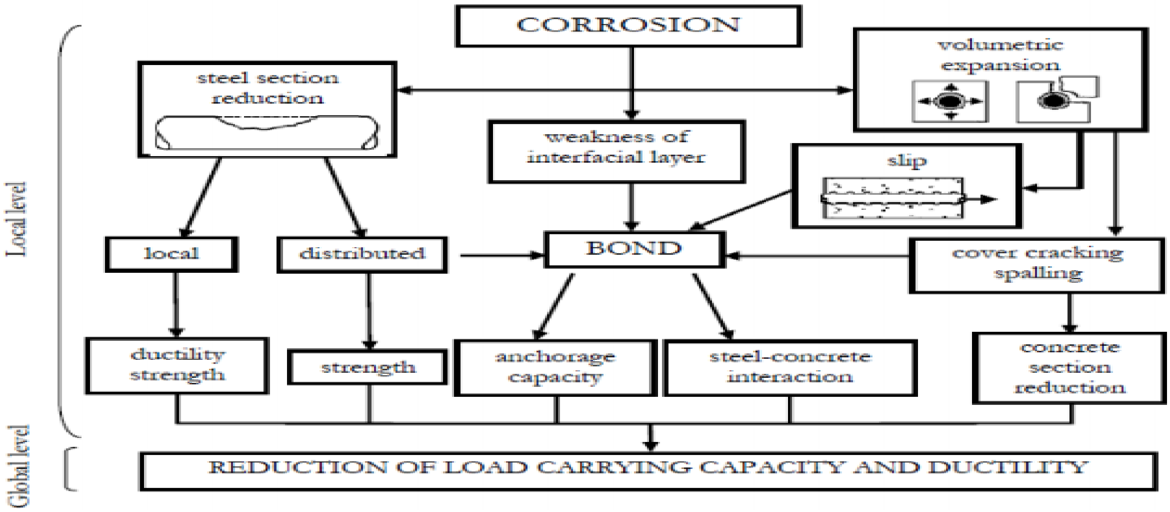

Figure 2. Corrosion effects on structural performance (Sonebi et al., 2011).

REASONS OF CORROSION

Carbonations

Carbon dioxide in atmospheric reacts with the calcium and alkaline hydroxides and cement, lead to decreasing of the PH value up to values about neutrality. This cause activation of the steel surface attached to the carbonated region. Carbonation is propagation into the concrete and therefore, its depth developed by a rapid debilitation along the time. The depth of carbonation does not progress if the concrete wet or in a too dry situation. (Stages et al.,2017).

Loss of alkalinity owing to chlorides

The entrance of ions of chloride on the RC structures damages the protective film layer protecting the rebars. The chlorides react with the calcium alumina to form calcium chloro-aluminates which is not water soluble. In this composition, chloride is restricted in passive shape. Commonly, this reaction is reversible and several energetic (Quraishi et al., 2017).

Sulfate Attack

Sulfate assault is the chemical reaction between the ions of sulfate from the ground-water and the various stage of hydrate cement hydrate, but chiefly calcium aluminate hydrate to produce ettringite, calcium sulfo-aluminate hydrate, or with calcium hydroxide to create gypsum. At the start, these productions may consequence in a void filling but in the end, it enlarges and cause concrete damage. Solid salts, such as sulfates, will not straightly rush concrete but, when in solution, they can react with certain ingredients of the cement paste cause enlargement, cracking and laminate of concrete. The most popular formation of sulfates are sodium sulfate Na_2SO_4, magnesium sulfate $MgSO_4$, potassium sulfate K_2SO_4, and calcium sulfate $CaSO_4$. The above sulfates are conventional in natural groundwater and may available soils or in the amalgamation. (Saleh, 2008).

CONSIDERATIONS IN THE DESIGN OF RC MEMBERS

It is possible to consider the corrosion allowances and be applied to the reinforcements in the design phase for the entire lifetime of the structures. The readers are referred to the references [37] to [64] for numerical simulation of the RC structural members considering the corrosion allowance, confined and unconfined concrete to quantify the dames to RC structural members.

CONCLUSIONS

An overview of the corrosion problems in RC structures including the causes, mechanism, effects, controls and evaluation are submitted. The different problems are classified and the considerations needed to be applied in the design and maintenance are suggested, which is useful for the designers.

REFERENCES

[1] Gonçalves, M.C., and Margarido, F. (2015). *Materials for construction and civil engineering.* Springer International Publishing, Cham.

[2] Ormellese M., Berra M., Bolzoni F., Pastore T. (2006). Corrosion inhibitors for chlorides induced corrosion in reinforced concrete structures. *Cement and Concrete Research 36*, 536-547.

[3] Apostolopoulos, C.A., and Pasialis, V.P. (2010). Effects of corrosion and ribs on low cycle fatigue behavior of reinforcing steel bars S400. *Journal of Materials Engineering and Performance, 19*(3), 385-394.

[4] Kashani, M.M., Lowes, L.N., Crewe, A.J., and Alexander, N.A. (2016). Computational modelling strategies for nonlinear response prediction of corroded circular RC bridge piers. *Advances in Materials Science and Engineering, 2016.*

[5] Wilmot, R.E. (2007). Corrosion protection of reinforcement for concrete structures. *Journal of the Southern African Institute of Mining and Metallurgy, 107*(3), 139-146.

[6] Turkish Seismic Design Code-TSDC (2007). *Regulations for buildings to be constructed in earthquake-prone areas.* Ankara: Ministry of Public Works and Settlement, Turkey.

[7] Ou, Y.C., and Nguyen, N.D. (2016). Influences of location of reinforcement corrosion on seismic performance of corroded reinforced concrete beams. *Engineering Structures, 126*, 210-223.

[8] Quraishi, M.A., Nayak, D.K., Kumar, R., and Kumar, V. (2017). Corrosion of reinforced steel in concrete and its control: An overview. *Journal of Steel Structures and Construction, 3*(1).

[9] Quraishi, M.A., Kumar, V., Abhilash, P.P., Singh, B.N. (2011). Calcium Stearate: A Green Corrosion Inhibitor for Steel in Concrete Environment. *J. Mater. Environ. Sci. 2* (4) 365-372

[10] Mehta P.K., Monteiro P.J.M. (2006). *Concrete Microstructure, Properties, and Materials.* USA: McGraw-Hill Companies, Inc.

[11] Neville AM (2005). *Properties of concrete.* Pearson. Prentice Hall, 255- 262.

[12] Tehada, T., and Hernandez, A. (2013). *Electrical Resistance Probe Corrosion Sensors for In-Situ Assessment for Waterfront Structures,* FY09 OSD Project F09NV04 (No. TR-NAVFAC-EXWC-CI-1301). Naval facilities engineering command port Hueneme Ca Naval facilities engineering and expeditionary warfare center.

[13] Brown, D.W., Connolly, R.J., Laskowski, B., Garvan, M., Li, H., Agarwala, V.S., and Vachtsevanos, G. (2014). *A Novel Linear Polarization Resistance Corrosion Sensing Methodology for Aircraft Structure.* Analatom, Inc. Santa Clara United States.

ISSN: 2223-9944, e ISSN: 2223-9553

[14] Grossi, M., and Riccò, B. (2016). Electrical impedance spectroscopy (EIS) for biological analysis and food characterization: a review. *Journal of Sensors and Sensor Systems 6*, pp.303 - 325

[15] Obot, I.B., and Onyeachu, I.B. (2017). Electrochemical frequency modulation (EFM) technique, Theory and recent practical applications in corrosion research. *Journal of Molecular Liquids, 249*, 83–96.

[16] Vedalakshmi, R., Manoharan, S.P., Song, H.W., and Palaniswamy, N. (2009). Application of harmonic analysis in measuring the corrosion rate of rebar in concrete. *Corrosion Science, 51*(11)

[17] Rivera, A.L., and Castaño, V.M. (2012). Corrosion analysis by electrochemical noise: A teaching approach. *Journal of Materials Education, 34*(5-6).

[18] Nayak, S. (2013). The analogue of potentiometer for current Zero Resistance Ammeter (ZRA). *Resonance, 18*(4).

[19] Enos, D.G., and Scribner, L.L. (1997). The potentiodynamic polarization scan. Solartron Instruments, Hampshire, UK, *Technical Report, (33).*

[20] Kawakam, Y., Kanaji, H., and Oku, K. (2011). Study on application of field signature method (FSM) to fatigue crack monitoring on steel bridges. *Procedia engineering, 14*.

[21] Zhou, J. (2011). *A study of acoustic emission technique for concrete damage detection.* Master's report, Michigan : Michigan Technological University,

[22] Kuang, F., Zhang, J., Zou, C., Shi, T., Wang, Y., Zhang, S., and Xu, H. (2010). Electrochemical Methods for Corrosion Monitoring: A Survey of Recent Patents. *Recent Patents on Corrosion Science, 2010.*

[23] Eun, S. (2004). *Hydrogen Sulfide Flux Measurements and Dispersion Modeling From Constr.* Florida: University of Central Florida. Orlando.

[24] Dinakar P, Babu K.G., Santhanam M. (2007). Corrosion Behaviour of blended cements in low and medium strength concretes. *Cement Concrete Composites 29*, 136-145.

[25] Zongjin, L. (2011). Advanced concrete technology. Hoboken, New Jersey, John Wiley and Sons, Inc.

[26] Broomfield, J.P. (1995). *Corrosion of steel in concrete: understanding, investigation and repair.* EandFN Spon.

[27] Yu, Y., Shi, X., and Yang, P. (2015). *Simulation on the steel galvanic corrosion and acoustic emission.* In Sixth International Conference on Electronics and Information Engineering (Vol. 9794, p. 97942E). International Society for Optics and Photonics.

[28] Überblick, N.B.E., and Aperçu, A.E.A.I.U. (2005). Stainless steel reinforcement–a survey. *Otto-Graf-Journal, 16*, 111.

[29] Prachasaree, W., Piriyakootorn, S., Sangsrijun, A., and Limkatanyu, S. (2015). Behavior and performance of GFRP reinforced concrete columns with various types of stirrups. *International Journal of Polymer Science, 2015*.

[30] Bashi, S.M., Mailah, N.F., and Radzi, M.M. (2003). *Cathodic protection system. In Power Engineering Conference, 2003.* PECon2003. IEEE, Proceedings. National, 366-370.

[31] Du, Y.G., Clark, L.A., and Chan, A.H.C. (2005a). "Effect of Corrosion on Ductility of Reinforcing Bars." *Magazine of Concrete Research, 57*(7), 407–419.

[32] Du, Y.G., Clark, L.A., and Chan, A.H.C. (2005b). "Residual Capacity of Corroded Reinforcing Bars." *Magazine of Concrete Research, 57*(3).

[33] Lundgren, K. (2005). "Bond between Ribbed Bars and Concrete. Part 2, The Effect of Corrosion." *Magazine of Concrete Research 57*(7).

[34] CEB-fib. (2000). Bond of Reinforcement in Concrete. State-of-Art Report, Fédération *Internationale du béton, Bulletin 10,* prepared by Task Group Bond Models, Lausanne, Switzerland

[35] Sonebi, M., Davidson, R., and Cleland, D. (2011). *Bond between Reinforcement and Concrete, Influence of Steel Corrosion.* In International conference on durability of building materials and components, Porto, Portugal.

[36] Saleh, A. (2008). *Chloride Induced Corrosion and Sulphate Attack-A Literature Review on Concrete Durability.* Institute of Concrete Technology (UK) Elkem Materials South East Asia, Singapore The 3rd ACF International Conference-ACF/VCA.

[37] Fatemi, A.A., Tabrizian, Z., Sadeghi, K. (2016). Non-Destructive Static Damage Detection of Structures Using Genetic Algorithm, *International Journal of Civil and Environmental Engineering, 3* (3), 1-5.

[38] Massumi, A., Sadeghi, K., Moshtagh, E. (2018). Effects of Deviation in Materials' Strengths on the Lateral Strength and Damage of RC Frames. *Structural Engineering and Mechanics, 68*(3), 289-297.

[39] Sadeghi, K. (1994). Proposition of a simulation procedure for the non-linear response of R/C columns or piles under oriented lateral loading. *International Journal of Engineering, 5*(2a), 1–10.

[40] Sadeghi, K. (1995). *Simulation numérique du comportement de poteaux en béton armé sous cisaillementdévié alterné.* Ph.D. Dissertation, Université de Nantes, Nantes, France.

[41] Sadeghi, K. (1998). *A New Formulation of Damage Indicator for Structures Subjected to Cyclic and Monotonic Loading*, Third International Conference on Coasts, Ports & Marine Structures (ICOPMAS98), Tehran, Iran.

[42] Sadeghi, K. (1998). Proposition of a damage indicator applied on R/C structures subjected to cyclic loading. *Fracture Mechanics of Concrete Structures, Volume 1*, 707-717.

[43] Sadeghi, K. (2001). *Proposition of a simulation procedure for the non-linear response of R/C columns under cyclic biaxial bending moment and longitudinal loading*. Proceedings of The First International Conference on Concrete and Development, 2, 233–239.

[44] Sadeghi, K. (2002). *Numerical simulation and experimental test of compression confined and unconfined concretes.* Water Resources Management Organization, Ministry of Energy, Concrete Laboratory of Power and Water University of Technology.

ISSN: 2223-9944, e ISSN: 2223-9553
www.journals.savap.org.pk

[45] Sadeghi, K. (2011). Energy based structural damage index based on nonlinear numerical simulation of structures subjected to oriented lateral cyclic loading. *International Journal of Civil Engineering, 9*(3), 155–164.

[46] Sadeghi, K. (2014). Analytical stress-strain model and damage index for confined and unconfined concretes to simulate RC structures under cyclic loading. *International Journal of Civil Engineering, 12*(3), 333-343.

[47] Sadeghi, K. (2015). Nonlinear numerical simulation of RC columns subjected to cyclic oriented lateral force and axial loading. *Structural Engineering and Mechanics, 53*(4), 745-765.

[48] Sadeghi, K. (2017a). Nonlinear Static-Oriented Pushover Analysis of Reinforced Concrete Columns Using Variable Oblique Finite-Element Discretization. *International Journal of Civil Engineering, 14*(5), 295-306.

[49] Sadeghi, K., Angın, M. (2018). Characteristic Formulas of Damage Indices for Reinforced Concrete Structures: A General Guideline. *Academic Research International, 9*(3), 8-18.

[50] Sadeghi, K., Lamirault, J. (1994). *A simulation procedure for the nonlinear response of R/C columns under oriented lateral loading,* International Symposium of Construction 2000, Romania.

[51] Sadeghi, K., Muhammad, S.M., Sofy, S.A. (2018). Constitutive laws for compression concrete under monotonic and cyclic loading: Characteristic models. *Academic Research International, 9*(2), 11-23.

[52] Sadeghi, K. (2017b). Nonlinear numerical simulation of reinforced concrete columns under cyclic biaxial bending moment and axial loading. *International Journal of Civil Engineering, 15*(1), 113-124.

[53] Sadeghi, K., and Nouban, F. (2010a). A New Stress-Strain Law for Confined concrete Under Cyclic Loading. *International Journal of Academic Research, 2*(4), 6–15.

[54] Sadeghi, K., and Nouban, F. (2010b). A simplified energy based damage index for structures subjected to cyclic loading. *International Journal of Academic Research, 2(*3), 13-17.

[55] Sadeghi, K., and Sadeghi, A. (2013). Local and microscopic damage indices applicable to RC structures and concretes subjected to cyclic loading. *International Journal of Academic Research, 5*(4), 216-221.

[56] Sadeghi, K., and Nouban, F. (2017a). Behavior modeling and damage quantification of confined concrete under cyclic loading. *Structural Engineering and Mechanics, 61*(5), 625-635.

[57] Sadeghi, K., and Nouban, F. (2017b). Global and Local Cumulative Damage Models for Reinforced Concrete Structures Subjected to Monotonic, Cyclic, or Fatigue Loading. *International Journal of Civil Engineering, 15*(7), 1063–1075.

[58] Sadeghi, K., and Nouban, F. (2017c). A Highly Accurate Algorithm for Nonlinear Numerical Simulation of RC Columns under Biaxial Bending Moment and Axial Loading Applying Rotary Oblique Fiber-Element Discretization. *International Journal of Civil Engineering, 15*(8), 1117–1129.

[59] Sadeghi, K., and Nouban, F. (2016). Damage and fatigue quantification of RC structures. *Structural Engineering and Mechanics, 58*(6), 1021-1044.

ISSN: 2223-9944, e ISSN: 2223-9553
www.journals.savap.org.pk

[60] Sadeghi, K., and Nouban, F. (2018). An algorithm to simulate the nonlinear behavior of RC 1D structural members under monotonic or cyclic combined loading. *Structural Engineering and Mechanics, 66*(3).

[61] Sadeghi, K., and Nouban, F. (2019). An algorithm for simulation of cyclic eccentrically-loaded RC columns using fixed rectangular finite elements discretization. *Computers and Concrete, 23*(1), 25-36.

[62] Sadeghi, K., Jacques, L., Sieffert J.G. (1993), Proposition de définition d'un indicateur de dommage, Troisième Colloque National de Génie parasismique "Génie parasismique et Aspects vibratoires dans le Génie civil". *AFPS, Volume 2*, Paris.

[63] Hashemi, S. Sh., Sadeghi, K., Vaghefi, M., Seyed A. Siadat (2018). Evaluation of ductility of RC structures constructed with Bubble Deck system. *Structural International Journal of Civil Engineering, 16*(5), 513–526.

[64] Hashemi, S. Sh., Sadeghi, K., Vaghefi, M., Seyed A. Siadat (2020). *Evaluation of the response modification factor of reinforced concrete structures using bubble deck slab, Scientia Iranica,* Articles in press, Accepted manuscript available online from 7 October 2018.

ISSN: 2223-9944, e ISSN: 2223-9553