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A Review on Life Cycle Cost Assessment of RC Structure Subjected to Corrosion

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Abstract: Corrosion of embedded reinforcement is one of the major problems that contribute to deterioration of structural concrete. The actions of corrosive environment, cyclic loading and concrete cracking lead to structural degradation. The interaction between these conditions can only be taken into account when modeling the coupled phenomena. Furthermore, corrosion, fatigue and crack propagation are phenomena affected by high uncertainties, where deterministic methods fail to predict accurately the structural life. In this paper, the Review has been done on life cost assessment investigations done by the prominent researchers.

Keywords: CORROSION, LIFE-365, PHASE. LCC, FRP.

I. INTRODUCTION

The Corrosion Process Corrosion is defined as “the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties” (ASTM terminology, G15). When reinforcement in concrete corrodes, the cross sectional area of steel reduces, which leads to failure of the concrete structures subject to tensile and flexural stresses. On a molecular level, chemical ions occur in cells where the anode and cathode are directly adjacent to one another. These are referred to as micro-cells. Anode- and cathode-corrosion cells separated by some distance are considered macro-cells. Generally, iron (Fe) atoms pass into solutions as positively charged (Fe2+) hydrated ions at the anodic site, and the liberated electrons flow through the metal to cathodic sites, where dissolved oxygen is available to consume them. The reactions that take place at the anode and cathode are presented below (Broomfield, 2007): At the anode: Fe → Fe2+ + 2eAt the cathode: 2e- + H2O + ½ O2 → 2OHThe process is expressed by equations below: Fe2+ + 2OH- → Fe(OH)2 4Fe(OH)2 + O2 + 2H2O → 4Fe(OH)3 2 Fe(OH)3 → Fe2O3•H2O + 2H2O. Life-cycle cost analysis able to be applied to choose optimal strategies improving durability of RC structures under various degradation processes. At long-term performance of RC structures, structural deterioration will be a major problem. The critical issue for several reinforced concrete structures is due to Corrosion induced by chloride ions. Fatigue may results in excessive deformations in concrete structures, excessive crack widths, debonding or rupture of reinforcement leading to structural collapse. The actions of corrosive environment, cyclic loading and concrete cracking lead to structural degradation. The interaction between these conditions can only be taken into account when modeling the coupled phenomena. Furthermore, corrosion, fatigue and crack propagation are phenomena affected by high uncertainties, where deterministic methods fail to predict accurately the structural life. The expected failure costs are directly linked to the probability of failure corresponding to each mode. The influence of uncertainties on the structural system and their impact on the life cycle cost analysis is observed. When it comes to degradation processes, corrosive environments and cyclic loading are among the main causes of reinforced concrete deterioration. Stewart et al. proposed a model to compute the reduction of the concrete section and the area of steel reinforcement in order to assess the change of structural capacity with time. El-Hassan et al. [4] proposed a reliability model to deal with initiation and propagation of RC corrosion, in order to determine the probability distributions of the time of corrosion initiation and the time to failure of RC members subjected to chloride ingress. E. Bastidas-Arteaga et al. considered the effect of coupled corrosion–fatigue on the deterioration of RC structures. The cost model proposed by Aissani allows us to consider the direct costs related to failure, as well as the indirect losses in terms of loss of human lives.

II. INVESTIGATIONS

In general, the basic concept developed by [*Tuutti 1982*], ('typical service life model'), is employed in all of the previously mentioned service life models and recommendations to determine the (residual) service life of reinforced concrete structures exposed to aggressive environments. According to [*Tuutti1982*] the service life of a structure is comprised of two distinct phases;

1) the initiation phase during which aggressive substances penetrate the concrete cover, eventually causing initiation of reinforcement corrosion and

2) the propagation phase, when reinforcement corrosion-induced damages cause an increased rate of deterioration.

Once corrosion is initiated, the rate of structural deterioration is often considerably increased compared to the initiation phase. The expansive nature of most of the solid corrosion products may result in the formation of cracks in the concrete cover, concrete spalling or delamination. Strength and serviceability of reinforced concrete structures may be further affected by the cross sectional reduction of the reinforcement leading in the worst case to failure. Therefore, extensive research has been carried out within the past decades studying and developing models and tools to describe mechanical degradation mechanisms of corroding reinforced concrete structures, see e.g. [*Bazant 1979, Andrade et al. 1993, Alonso et al. 1998, Liu et al. 1998, Noghabai1999, Ouglova et al. 2006, Caré et al. 2008, Chernin et al. 2009, Val et al. 2009*].

More recently, the research community also placed focus on studying the corrosion processes in reinforced concrete structures once corrosion is initiated and developed models to describe the propagation phase, see e.g. [*Jäggi 2001, Kranc et al. 2001,Maruya et al. 2003, Ouglova et al. 2005, Isgor et al. 2006, Osterminski et al. 2006,Warkus et al. 2006, Warkus et al. 2008*].

Although the aforementioned service life models and recommendations are generally accepted and used in civil engineering for the design of durable reinforced concrete structures, several key issues remain that must be included in service life modelling for a more accurate qualification and quantification of the service life of concrete structures. As mentioned earlier, the end of service life is defined by a limit state at which either repair/maintenance or deconstruction of the structure is required. Current service life models (see e.g. DuraCrete, *fib*, Life-365, 4sight, and Hetek) describe the (residual) service life of reinforced concrete structures analysing the ingress of aggressive substances into the concrete.

Once a defined limit state is reached, e.g. a critical chloride threshold in case of chloride-induced corrosion, the initiation phase of reinforcement corrosion and often the service life of a reinforced concrete structure is ended. In some cases, non-commercial service life models consider the propagation phase (e.g. Life-365, *fib*), although only as a fixed length of time [*Life-365 Consortium II 2010*] or based on expert opinions *[fib Bulletin 34 2006*].

C. M. Hansson, A. Poursaee, S. J. Jaffer Investigated on the causes and mechanisms of corrosion of reinforcing bars in concrete are described in terms of the practical issues as well as the electrochemistry. The parameters affecting corrosion are (i) the ingress of aggressive species, such as chlorides, which break down the protective film on the reinforcing bar and (ii) the amount of those species necessary to do so. The former is largely controlled by the concrete properties while the latter is a function of the type and condition of the reinforcing bar. Thus, the influence of the cementitious components of concrete, the water/cementitious materials ratio and the presence of cracks in the concrete cover, on the ingress of aggressive species is considered and the various currently available reinforcing bar materials and their merits are reviewed.

Portland cement concretes provide excellent protection for embedded steel in the absence of chloride contamination or carbonation by (a) acting as a physical barrier and (b) by chemically passivating the steel surface. Nevertheless, reinforcing bar corrosion is a major cause of the degradation of reinforced concrete structures particularly in northern North America, because of the high quantities of chloride de-icing salts used. In addition the increase in construction near coastal marine environments may increase the potential for corrosion deterioration in these areas. As a result, some structures of ordinary portland cement concrete with black steel reinforcement are requiring repair and remediation long before their current specified service lives (typically 40 – 50 years) are reached. Therefore, easier, faster and more reliable condition analysis techniques are required than those currently available, and described, to allow corrosion detection at an earlier stage and, thus, permit remedial action to be taken before major repairs are required. At the same time, with the current emphasis on sustainability, building codes are now requiring longer service lives, of the order of 75 to 100 years. Consequently, for new structures, there must be a greater understanding of the reinforcement corrosion process and of materials and structural designs aimed at minimizing the risk of corrosion.

Mohamed R. Sakr, Karim El-Dash, Osama El-Mahdy Investigated that,the Chloride induced corrosion is the main cause of deterioration of reinforced concrete structures in marine environment. Corrosion damages require huge expenses to be repaired. Thus, it is required to design structures that need less repair in their life. A model to estimate Life-Cycle-Cost (LCC) of reinforced concrete structure in marine environment is proposed to be used as either an evaluation tool of a certain design, or as selection tool between suggested designs. It is concluded that life-cycle-cost analysis is an important tool to be used in assessing different specifications. Also, basing the decision upon the initial investment only can lead to an erroneous judgment. The total cost through the intended life has to be considered to choose the cost-effective solution as low initial investment can mean high maintenance and repair cost where the total cost may exceed high investments with low maintenance and repair costs.

A model to estimate life cycle costs of reinforced concrete structure in marine environment is proposed. It is concluded that life cycle cost analysis is an important tool to be used in assessing different specifications. Also, basing the decision on the initial investment only can lead to an erroneous judgment, and the total cost through the intended life has to be considered to choose the cost-effective solution as low investments can mean high maintenance and repair costs where the total cost can exceed high investments with low maintenance and repair cost.

Ha Lix,Daewon Seo, Byumseok Han, Sukhyeong Yoo, Sungwoo Shin, and Han-Seung Lee presents simple methodologies for evaluating comparative life cycle costs for concrete structures using conventional and FRP rebars.

Based on this study, it appears that FRP rebars can offer benefits to the construction industry. Although initial costs of FRP rebars are likely to be higher than those of steel reinforcement, there is a significant potential for cost savings due to reduced maintenance cost. The maintenance costs are due to the corrosion resistance of the FRP rebars. The results of the cost analysis presented in this paper show that when direct life cycle costs are considered, in many cases FRP rebars already constitute an economically competitive alternative to conventional steel reinforcement. If, in addition, the savings owing to environmental and other indirect costs associated with maintenance operations are considered, the proposed FRP rebars are even more competitive.

Mark G. Stewart, Jianxin Peng describes a reliability-based approach that predicts the probability of corrosion initiation and damage (severe cracking) for RC structures subjected to corrosion resulting from concrete carbonation when atmospheric CO2 concentration and temperature increases with time over the next 100 years based on the latest IPCC report for climate change. Increasing design cover is a suggested climate change adaptation strategy. A life-cycle cost analysis is then conducted that considers costs associated with extra design cover and expected maintenance/repairs for typical RC structures and elements over the next 100 years considering several IPCC atmospheric CO2 emission scenarios. If the proposed increases in design cover produce a minimum life-cycle cost then increasing design cover will be a cost-effective measure to mitigate the effects of carbonation-induced corrosion damage. It was found that life-cycle costs for the current situation (‘do nothing’ – use existing covers) are lower than life-cycle costs for proposed increases in design cover. This suggests that although enhanced greenhouse conditions will lead to increased carbonation-induced corrosion of RC structures it may not be cost-effective to increase design covers

Global warming and climate change studies show that greenhouse gas emissions (atmospheric CO2) may more than double this century. The paper described a reliabilitybased approach that predicts the probabilities of corrosion initiation and corrosion damage (severe cracking) and the recommended increase in design cover to offset the effects of increasing CO2 concentrations and associated increase in temperatures. A life-cycle costs analysis considered initial construction costs and the costs of providing extra design cover and expected maintenance/ repairs for typical RC structures and elements over the next 100 years considering several IPCC atmospheric CO2 emission scenarios. It was found that life-cycle costs for the current situation (use existing covers) are lower than life-cycle costs for proposed increases in design cover. This suggests that although enhanced greenhouse conditions will lead to increased carbonation-induced corrosion of RC structures it may not be cost-effective to increase design covers.

Ranjith A,K Balaji Rao And K Manjunath presents review of some of the recent service life models for existing as well as repaired concrete structures, developed through these computational tools. In recent years, substantial efforts were made by the researchers in developing various service life prediction models due to the advancement in computer knowledge and material science. Researchers have used various methods like ANN, FEA, FDM, fuzzy approach and Probabilistic approach. However, expertise is needed in developing computational model. FEA method in assessing the performance of deterioration mechanisms is very popular among researchers since, this methodology enable faster simulation and best possible outcomes compared to conventional methods. However, most of the constitutive relations and boundary conditions are not yet known for the interface between original concrete and repair material, hence it is very difficult to assess the efficiency of repair strategy and hence the structural performance. If corrosion is extensive or minimum fuzzy approach is better in handling uncertainties arising due to the use of linguistic terms to describe exposure and quality of construction. Probabilistic approach is better and reliable as it considers uncertainties in the parameters responsible for deterioration by identifying the variables to be included in simulation with respect to different responses based on sensitivity study. Markov chain models are useful when very few inspection data is available. Bayesian belief networks are simple to use when to update probability. Neural network tools are efficient in assessing degradation performance of structure when there may be many variable parameters affecting the degradation of concrete.

Neal S. Berke And Arnold Rosenberg presents that the Calcium nitrite has been used as a corrosion inhibitor against chloride attack and as a set accelerator in concrete for more than 20 years. Considerable data are available concerning its effects on corrosion inhibition, setting times, freeze-thaw resistance, strength, and other properties. Although much of the data have been published in the open literature, a full-scale review is not available. This paper reviews past and present research on the properties of calcium nitrite in concrete. While the bulk of the data have been generated by W.R. Grace & Co., considerable information is available from outside sources, including the U.S. Federal Highway Administration (FHWA), departments of transportation, universities, and independent test laboratories. It is shown that calcium nitrite is an effective corrosion inhibitor for steel in concrete, based upon extensive corrosion testing in laboratory and field concrete specimens. The effects of mix design and concrete cover on corrosion resistance with calcium nitrite are also discussed. Furthermore, in most cases, calcium nitrite improves the compressive strength of the concrete mix and, with proper air entrainment, is freeze-thaw durable. In conclusion, the data generated in the last 20 years show that calcium nitrite is a proven corrosion-inhibiting admixture to be used to protect concrete structures in a chloride environment.

Gerardo G. Clemeña summarizes the major conclusions drawn from its companion reports, which described investigations conducted using a stainless steel–clad bar, selected stainless steel bars (304, 316LN, and duplex 2205), and a carbon steel bar in concrete and in simulated concrete pore solutions (with various concentrations of chloride and pH) to assess the comparative corrosion resistance of the clad bar. The most important conclusion is that stainless steel cladding serves as an excellent protection for the carbon steel core. The clad bars and the solid stainless steel bars tolerated the same concentration of chloride ions without corroding, a level that was at least 15 times more than the corrosion threshold for carbon steel bars. Simple cost comparisons demonstrated that the clad bar is also a cost-effective reinforcement for extending the service life of future concrete bridges. Based on its excellent corrosion resistance and reasonable price, the study recommends that the clad bars be used in the construction of new concrete bridges in Virginia as long as the mechanical and physical characteristics of the bars are at least equivalent to those specified by the American Society of Testing and Materials in ASTM A 615.

Alberto A. Sagüés ,Rodney G. Powers And Richard Kessler found that the Severe corrosion of epoxy coated rebar in the substructure of 5 major marine bridges in the Florida Keys was detected after only a few years of construction. Corrosion occurred underneath the coating and was preceded by loss of adherence between the steel and the coating. Damage surveys of the bridges, which were built around 1980, were conducted from 1986 to 2000. Corrosion resulted in delaminated areas (spalls) typically about 0.3 m2 each. After Initial detection, damage has been steadily accumulating at a rate of approximately 0.1 spall per bridge pier (bent) per year. An initiation-propagation model for corrosion development reproduced the observed trends. The exploratory model assumes distribution of chloride diffusivity, rebar cover, chloride surface concentration, and propagation time. Interpretation of the results suggests that much of the early damage stemmed from rebar with high levels of coating distress, and that damage development depends mainly on the propagation stage of corrosion.

P. S. Mangat B. T. Molloy presents a wide range of experimental data of the authors and of other researchers on acid-soluble chloride diffusion in different mixes of concrete, and shows conclusively that the chloride diffusion coefficient D_c is strongly dependent on the period of exposure of concrete to a chloride environment. Consequently, long term prediction of chloride concentrations on the basis of Fick's second law of diffusion, which inherently assumes a constant value of D_c, is not an accurate procedure. A differential equation is derived based on the above law of diffusion, which takes into account the time variation of D_c, and a procedure is outlined for the accurate prediction of long term chloride concentrations in concrete. The chloride concentration profiles derived using this procedure show good correlation with experimental data.

Pierre Che Ho Pun investigates the influences of silica fume and WKM ratio on the chloride resistance of concrete. Other factors studied were curing regimes and different coarse aggregates. The main tests used for evaluation were bulk diffision tests, standard AASHTO T259 sait ponding test, and rapid chioride permeability test. 7% silica fume replacement was found to be more effective than reducing W/CM ratio from 0.15 to 0.35 in enhancing the durability of concrete. Good correlations between the different chloride penetration resistance tests were also established.

Yun-Fen Feng, Jin-Xin Gong, Xiao-Yan Yang investigated about the main cause of deterioration in reinforced concrete (RC) structures is related to reinforcing steel corrosion, therefore, the calculation of steel corrosion loss should be evaluated in detail. The corrosion initiation time and concrete cracking time are random variables due to the various uncertainties in reinforcement corrosion process. Thus, RC structural member at a specific observation time of design period may be in three different states, namely no corrosion, ongoing corrosion but no cover concrete cracking, concrete cover cracking. Accordingly, a probabilistic model for corrosion loss of steel cross-section was developed in three critical phases. For illustrative purpose, statistic analysis of the percentage of corrosion was conducted using Monte Carlo simulation for a simply supported RC flexural member, in which the occurrence probabilities of above three different states at an observation time were determined. The statistical results showed that percentage of corrosion can be described by a double-peak probability distribution; the occurrence probabilities of no corrosion and no concrete cracking decrease with time; the reliability of RC flexural element in marine environment significantly decreases with time due to reinforcement corrosion.

In real structures, concrete is always cracked due to various mechanisms such as drying shrinkage, chemical attack, thermal gradients, freezing-thawing cycles, alkali-aggregate reaction and external loading. L.C. Wang, J.Z. Wang realized that cracking can significantly accelerate the deterioration of reinforced concrete structure because it provides preferential flow channels and allows more chlorides to penetrate. This paper aims to illustrate the effect of external loading or cracking of concrete on the chloride diffusion rate by numerical simulation method. The lattice network model on mesoscopic composite structure of concrete is used to evaluate the diffusion properties of cracked concrete, while the Rigid Body Spring Model (RBSM) is adopted to quantify the parameters of cracking, such as the crack number and width. The chloride diffusion coefficient through a single crack is determined as 10000 mm^2/h when crack width is larger than the critical value and 3000 mm^2/h when smaller than this critical value. Different flexural loading levels are applied to the concrete beam samples in order to obtain different damage degree in concrete. By means of a series of calculations, it is indicated that loading can significantly increase the chloride diffusion rate and penetration depth in concrete. Comparison with available test data shows that the proposed model can to some extent reflect the loading effect on chloride diffusion, particularly under higher loading levels than those applied in the test.

III. CONCLUSION

From the above review it has been observed that

Enhanced greenhouse conditions will lead to increased carbonation-induced corrosion of RC structures Increasing design cover is a suggested climate change adaptation strategy

RC structural member at a specific observation time of design period may be in three different states, namely no corrosion, ongoing corrosion but no cover concrete cracking, concrete cover cracking.

The effect of external loading or cracking of concrete on the chloride diffusion rate by numerical simulation method.

Easier, faster and more reliable condition analysis techniques are required than those currently available, and described, to allow corrosion detection at an earlier stage and, thus, permit remedial action to be taken before major repairs are required

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