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Calculation of Mass Loss on Corrosion of Reinforcement through Field Measurement

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ABSTRACT

Concept of reinforced concrete (RC) to be a durable material has been changed in last few decades as many RC structures are found showing distresses like cracking, spalling, de-laminations etc. The possible reason may be due to corrosion of reinforcement in costal chloride laden environment as well as in industrial CO₂ laden areas. Corrosion of reinforcement inside the concrete is not visible unless there is crack formation. After the formation of crack in concrete the residual life of the structural member is hardly 5 to 10 years. But corrosion of reinforcement inside the concrete can be known instrumentally from early stage before making any structural damage. For calculation of residual strength of RC members for integrity appraisal, many models have been proposed. However, accuracy of the model depends on the amount and distribution of corrosion of reinforcement in existing structures. This is also a difficult process to assess the above parameters. Present study discusses various methods for corrosion measurement in the field to the real structures and calculations of corresponding mass loss. This mass loss can be utilized satisfactorily for calculation of residual flexural strength of RC member in flexure on bond loss as well as strength loss on corrosion.

Keywords: Corrosion; mass loss; strength loss; durability; residual strength.

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INTRODUCTION

Many RC structures which are exposed to weather such as bridges, offshore structures and buildings etc. are found to show the premature distress before reaching their design life period. Reason may be many folded, such as aging, lack of maintenance, bad workmanship during construction that leads to rapid degradation of material strength and corrosion to the reinforcement. Maintenance of concrete structures generally gets neglected because of the prevailing misconception that the structure once constructed do not need any substantial maintenance. particularly in the first couple of decades after construction. The corrosion of reinforcement in concrete is found to be the principal reasons for damage and early failure of those reinforced concrete structures. Hence, the deteriorated structures require special care thereby leading to enormous cost for inspection, maintenance, restoration and replacement of infrastructure worldwide¹. Apart from problems of serviceability such as cracking and rust straining, corrosion of reinforcement causes significant change in static and dynamic behavior leading to reduction of their mechanical capacity². Thus, corrosion of steel reinforcement severely decreases the service life of reinforced concrete structure. Repair is necessary for the damages resulting from corrosion deteriorated structures is costly. As rehabilitation of those structures consumes more than 50% of initial construction cost³.

In developing countries like India, to carry out the repair work to all the structure as soon as any defect is detected or to carry repair and rehabilitation work at a time for the deteriorated structures is difficult due to limited resources. Generally, those works are carried out in priority basis depending on the religious and or socio-economic importance. Hence, there is growing need of reliable methods to predict the existing load carrying capacity and remaining service life of deteriorated RC to serve as basis of decision for optimum maintenance and repair strategy. Many structures experimental studies have been carried out to assess the load carrying capacity of corrosion affected structural elements based on flexure, shear, bond and fatigue etc. by conducting nondestructive testing. Also for further use in appraisal rating calculation⁴. Detailed guidelines on assessment of residual strength of naturally corrosion-damaged RC structures will be of a great importance to number of practicing and practitioners responsible for assessing and maintaining the corroded RC structures. The model should use damaged material properties accounting for amount of corrosion, exposed bar length, concrete loss, bond failure and types of stress incurred in reinforcement. Model accuracy depends on the accuracy of measured parameters in the field. Many researchers have proposed different formulas to calculate existing strength of naturally corroded reinforcement which involves the mass loss on corrosion. For calculation of mass loss precisely, also many researchers have proposed different methods and different types of devices have been commercially. Interpolation of results of field measurement for precise value of developed parameters has great importance.

Few complete methods have been proposed to utilize the corrosion monitoring data such as (I_{corr}) corrosion current, mass loss (ML) etc. to calculate bond loss, strength loss in reinforcement and corresponding flexural strength loss as per current Indian standard. Therefore, the objectives of the present investigations are summarized as: to study the different existing methods of corrosion monitoring for calculation of corrosion current (I_{corr}) of existing structures subjected to reinforcement corrosion. To study the different methods suggested by authors to calculate the mass loss from corrosion current (I_{corr}). To study the methods of calculation of residual strength of naturally corroded reinforcement proposed by different researchers. Finally, to coordinate above three studies to find a complete procedure to calculate the residual strength of corroded reinforcement of existing structures from corrosion monitoring data obtained by utilizing commercially available

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devices in practice. Present study involves the study of existing literature on fundamentals of corrosion of reinforcement in concrete, monitoring of corrosion in existing corroded structures by different commercially available devices, interpolation of monitoring data for calculation of mass loss and calculation of residual strength of corroded reinforcement from mass loss on corrosion.

LITERATURE REVIEW

The performance of reinforced concrete damaged as a result of reinforcement corrosion is a matter of great concern to those who are responsible for assessing and maintaining the corroded RC structures. Considerable research effort has been dedicated to know and understand the mechanisms and causes of reinforcement corrosion in concrete. Studies on residual strength of corroded reinforcement, ductility, bond strength and also finding the residual strength of structural members subjected to reinforcement corrosion has been carried out considerably. Review of existing literature on corrosion of reinforcement due to chloride ingress and carbonation, corrosion monitoring and calculation of mass loss is presented in subsequent sections.

CORROSION

Mechanism of Reinforcement Corrosion in Concrete

Corrosion in steel reinforcement in concrete is an electrochemical process⁵. When there is an electric potential difference along reinforcing bars an electrochemical cell is set up. Anodes and cathodes are created on reinforcement and those are connected by electrolyte which is the pore water present in hardened concrete. Fe⁺⁺ ions at anode pass into solution (anodic reaction) while free electrons e pass through the steel in to cathode where they are combined with water and oxygen to form hydroxyl ion (OH) (Cathodic reaction). (OH) ions travel through electrolytes (pore water) and combine with ferrous ion at anode to form ferrous hydroxide Fe(OH)₂ . Those hydroxides are converted into to rust on further oxidation. Following primary reactions are described⁶ (1) Fe \rightarrow Fe⁺⁺ +2e⁻ (Anode Reaction); (2) 4e⁻ + O₂+ H₂O \rightarrow 4(OH)⁻ (Cathode $(3)Fe^{++} + 2(OH)^{-} \rightarrow Fe(OH)_2$ (Ferrous hydroxide) and is presented in figure 1.At Reaction): anode Fe(OH)₂ is combined with oxygen to form Hydrated Ferric oxide (Fe₂O₃ H₂ O)(red green rust), Fe₃O₄(OH)₂ (green hydrated magnetite) and finally Fe₃ O₄. Those secondary reactions are given as (1) 4 Fe(OH)₂ +2H₂O+O₂ \rightarrow 4Fe(OH)₃ (Ferric hydroxide) (2) 2 Fe(OH)₃ \rightarrow Fe₂O₃. H₂O⁺+ 2H₂O.



Figure 1: Anode and Cathode reaction of reinforcing steel⁶

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Formation of Passive Layer around the Reinforcement

In newly prepared concrete, reinforcement is protected from corrosion physically by cover of good quality concrete and chemically by formation of insoluble thin protective film of iron oxide called passive layer on the surface of steel bars. A good quality fresh concrete free from chloride is highly alkaline having pH in range of 12.5-13.5. In these circumstances rusts such as FeO, Fe₃O₄, Fe₂O₃ and Fe (OH₃) are formed depending on supply of oxygen and other conditions. Those rusts form stable film called passive layer that prevents the corrosion of reinforcement at early stage⁷.

Break Down of Passive Layer

Passive layer is broken down principally due to chloride penetration and carbonation. For chloride ingress authors have reported three general models. The first one is adsorption-displacement model⁸. They reported that the breakdown of the passive layer is due to adsorption of Cl⁻ ion with displacement of O_2^{-} ion from passive film. Second model is chemical- mechanical model⁹. He reported that presence of Cl⁻ ion reduces the interfacial surface tension and there are formation of cracks and flows when repulsive forces between adsorbed ions are large enough. This phenomenon weakens the passive film deteriorate it. The third model is migration –penetration model¹⁰, which was developed and reported that ion migration takes place through ion exchange process between citation vacancy of O_2^{-} or OH⁻. When the Cl⁻ reaches the steel bar and occupies above vacancy, it forms complex with Fe^{2+.} Due to faster ion dissolution in passive layer creates voids which lead the formation of pits. Adsorbed Cl⁻ ion displaces the OH⁻ ion and forms soluble iron complexes¹¹. Thus, the conversion of amorphous layer into crystalline layer causes localized acidification and break down of passive layer.

Process of Chloride Diffusion into Concrete

The concomitant presence of hot humidity and high amount of air borne as well as water borne chloride creates an aggressive environment which is highly conductive to the corrosion to the reinforcement in chloride laden areas. Even there is no chloride in the concrete at the time of construction; the gradual built up of chloride takes place up to the threshold level slowly from external sources. Corrosion mechanism due to presence of chloride is presented in figure 2.



Figure 2 Chloride induced corrosion¹²

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Two dominant mechanism of chloride transport which depends on moisture content present in concrete, are described here. First one is absorption mechanism which consists of intrusion of chloride bearing water in to the capillary pores of unsaturated (dry) concrete. Chloride building in concrete by absorption depends on permeability and alternate wetting and drying condition and becomes dominant if dry concrete is wetted by chloride bearing water. The other one is diffusion. This mechanism is most dominant and migration of chloride takes place through pore water due to concentration gradient. Most of the researchers agreed that diffusion is the basic transportation mechanism of chloride in moist structure¹³⁻¹⁸.

Chloride Binding, Chloride Threshold and Corrosion Initiation Time

Initially CI⁻ is bound by the C₃A (tri calcium aluminates) present in concrete, forming a complex which is known as Friedel's salt ([$(Ca_2Al(OH)_6]$.2H₂O). This is called the chloride binding capacity of concrete. This process goes on until the chloride binding capacity of the concrete is exhausted. Further, ingress of chloride appears as free chloride also called as water solvable chloride which is responsible for corrosion of reinforcement^{15,18,19,20}. Total chloride content in the concrete is known as acid soluble chloride as it is found by acid soluble method. The chloride threshold is defined as the chloride concentration at steel concrete inters face that initiates the corrosion. Chloride concentration and the chloride threshold is expressed in term of percentage of chloride to the weight of cement. Threshold value depends on many factors of steel concrete system such as; chemistry and pH of pore solution, w/c ratio of the concrete, and composition of concrete such types of cement, additives etc., pore and capillary structure and curing procedure and exposed temperature, and Cl /OH in pore solution. Several researchers have found several different values as narrated below. Total chloride content in term of percentage weight of cement 0.17 to 2.5 for outdoor as well as laboratory condition in concrete and mortar¹⁹. However, 0.35 - 1.0% by weight of cement reported by other researcher¹⁶. The same is 0.05 - 0.7% by weight of cement for Middle East environment²¹. Maximum limit of 0.3% by weight of cement has been suggested by ACI²² for water soluble chloride in reinforced concrete. However, universal value is far from the actual^{15, 20}.

Growth of Rust Film

Those corrosion product (oxides) poses increased volume depending upon level of oxidation and the increase in volume is 1.7 to 6.15 times the original volume of iron involved in corrosion process .In general the composition of expansive corrosion product may be expressed as $(xFe(OH)_2+yFe(OH)_3+zFeH_2O)$, where, x, y and z are variables depending upon alkalinity of pore water inside the concrete, moisture content and supply of oxygen. Different corrosion product have different volume expansion as presented in Table 1.This increased volumes are identified as principal cause of expansion and corresponding expansive pressure in concrete leads to cover cracking.

Name of the rust	FeO	Fe ₃ O ₄	Fe ₂ O ₃	Fe(OH) ₂	Fe(OH) ₃	Fe(OH) ₃ 3H ₂ O
α	0.777	0.724	0.699	0.622	0.523	0.347
α ₁	1.8	2.0	2.2	3.75	4.2	6.4

	Table1:	Weight ratio a	and volume e	expansion ratio	of corrosion	products ²²
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where, α =Ratio of molecular weight of iron to that of corrosion product.

 $\alpha_{1=}$ Ratio volume of expansive product to that of iron consumed in corrosion process.

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Break Down of Passive Layer due to Carbonation

CO₂ present in atmosphere changes to dilute carbonic acid and penetrate into concrete. It react with Ca (OH) and forms relatively CaCO₃ and thus reducing the alkalinity (pH value) of concrete. The chemical reaction is given as Ca (OH)₂+CO₂ \rightarrow CaCO₃+H₂O. CO₂. On carbonation of all Ca (OH)₂, pH value reduces to 8.3 and in such a low pH value passive layer is destroyed and reinforcement is exposed to corrosion⁵. There is low diffusion of CO₂ when the pore of concrete is filled with water. On the other hand, on low relative humidity, pores remain dry and the CO₂ does not react with Ca (OH)₂ in hydrated cement . Thus, the rate of carbonation is maximum at a relative humidity between 50-70%.

CORROSION MONITORING AND CALCULATION OF CORROSION CURRENT

Assessment of residual capacity, maintenance and planning for the restoration of structures effected with reinforcement corrosion need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage. Properly monitoring the structures for corrosion problems and taking suitable measures at the appropriate time could effect enormous saving^{23, 24, 25, 26}. Many electrochemical and non-destructive techniques are developed for it .Out of which linear polarization resistance (LPR) measurement and Tafel extrapolation are reliable methods to measure corrosion current and which can be related to mass loss on corrosion using Faraday's law .

Linear Polarization Resistance

The linear polarization resistance (LPR) method to determine corrosion rate of reinforcement appears to be most accepted one²⁴. It is a well-established method of determining the instantaneous corrosion rate measurement of reinforcing steel in existing concrete^{25, 26, 27}. Draft standard test methods technique basically involves measuring the change in the open-circuit potential of the short-circuited electrolytic cell when an external current is applied to the cell²⁸. For a small perturbation about the open circuit potential, there is a linear relationship between the change in voltage, ΔE , and the change in applied current per unit area of electrodes, Δi . This ratio is called the polarization resistance (Rp),

 $R_p = \frac{\Delta E}{\Delta i}$

(1)

The current is expressed per unit area of electrode that is polarized, hence the units of R_p is ohms times the area. It has been pointed out that R_p is not a true resistance in the usual sense of the word but the term is widely used. It has been established underlying relationships between the corrosion rate of the anode and the polarization resistance and is derived from the slopes of the anodic and cathodic polarization - corrosion curves^{31, 32}. The corrosion rate which is also known as corrosion current density, i.e., current per unit area is inversely proportional to the polarization resistance given as follows as per Tafel's plot²⁹.

 $i_{corr} = \frac{B}{R_p}$ (2) where i_{corr} = corrosion current density, in ampere/cm² and B = a constant which represents characteristic of the polarization curves and a value of 26 mV is commonly used for steel²⁵.

Commercial linear polarization device with three/ four electrode system are available. A comparative study, involving laboratory and field tests, was conducted with commercially available 3 LP and 4LP

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corrosion rate meter²⁴ and was found that the 4LP device gave corrosion rates closest to the true corrosion currents measured independently by standard polarization resistance techniques. All the devices were capable of distinguishing between passive and active sites.

The device with sensor control has following recommended interpretation			
Corrosion current (I _{corr})	Condition of the rebar		
$I_{\rm corr} < 0.1 \mu A/cm^2$	Passive condition		
$I_{corr}0.1 - 0.5 \ \mu A/cm^2$	Low to moderate condition		
$I_{corr}0.5 - 1.0 \ \mu A/cm^2$	Moderate to high corrosion		
$I_{\rm corr} > 1.0 \mu {\rm A/cm^2}$	High corrosion rate		
The device with out sensor control has following recommended interpretation			
$I_{\rm corr} < 0.2 \mu {\rm A/cm^2}$	No corrosion expected		
$I_{\rm corr} 0.2 - 1.0 \ \mu {\rm A/cm^2}$	Corrosion possible 10 -15 years		
$I_{\rm corr} 1.0 - 10.0 \mu {\rm A/cm^2}$	Corrosion possible 2 -10 years		
$I_{\rm corr} > 10.0 \mu {\rm A/cm^2}$	Corrosion possible 2 years or less		

Table 2: Corrosion current vs. corrosion condition for the rebar

In spite of certain limitations in the method , based on years of experience from laboratory and field testing, the guidelines given in Table 2 have been developed for interpreting corrosion rate measurements using the guard ring device as well as 3 LP device. The corrosion current densities calculated as above can be converted to mass loss of steel by using Faraday's law³⁰. For example, 1 μ A/cm² corresponds to about 0.012 mm/year of section loss of reinforcing bars assuming the uniform corrosion on the bar (to be taken mass loss calculation). This is the typical condition for corrosion induced due to carbonation. Chloride-induced corrosion, however, is associated with pitting corrosion or localized corrosion.

Tafel Extrapolation

The Tafel extrapolation technique (TP) is another electrochemical method for measuring the rate of corrosion based on the intensity of the corrosion current (I_{corr}) and the Tafel slopes. Tafel slopes also could be used to calculate corrosion rate with LPR. Both LPR and TP techniques are based upon application of either galvanostatic or potentiostatic method in LPR method as described above. In TP, corrosion current (I_{corr}) can be calculated using straightforward substitution of Tafel slope values (βa and βc) as given in Eq. 3 then, corrosion rate can be calculated using the Eq. 4 $i=i_{corr}\{exp[S_1(E-E_{corr})]-exp[-S_2(E-E_{corr})]\}$ (3)

Where S₁=slope of the anodic branch=2.303/ β a, S₂=slope of the cathodic branch=2.303/ β c, β a=anodic Tafel constant, β c=cathodic Tafel constant, E_{corr}=the corrosion potential, i_{corr}=the corrosion current in Ampere, E=the potential at any time, and i=the current at any time.

(4)

Corrosion rate (
$$\mu$$
m/yr) = $\frac{0.129I_{corrEW}}{dA}$

where I_{corr} =the corrosion current intensity, in μ A/cm²; A=exposed surface area of the reinforcing steel, in cm; E.W.=the equivalent weight of steel, which is the atomic weight of an element that has the same combining capacity as a given weight of another element, where the standard is 8 for oxygen; and d=the density of the reinforcing steel, in g/cm³.To calculate the corrosion rate using the

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LPR method, I_{corr}is first calculated with Eq. 5 which is based on the Stern–Geary relationship. And then, using Eq. 4 the corrosion rate can be calculated³².

 $I_{corr} = \frac{\beta_a \beta_c}{2.3 R_P (\beta_a + \beta_c)}$

where Rp is the polarization resistance, in k Ω cm², and β a and β c are constants, which could be obtained from a Tafel Plot. To simplify the above calculation, some researchers have used Eq. 6 with a constant value, B, equal to 26 mV³³.

(6)

(7)

(11)

(5)

This method offers some significant advantages; under ideal conditions, the accuracy of the Tafel Extrapolation is equal or greater than conventional weight loss methods and with this technique it is possible to measure extremely low corrosion rates and it can be used for continuous monitoring of the corrosion rate of a system.

CALCULATION OF CORROSION CURRENT AND MASS LOSS

The mass of the steel that is consumed in corrosion process is related to the amount of the current that flows through the electrochemical corrosion cell .The Faraday's law have been used by several researchers to estimate the loss of mass of steel from applied current density, and also its ability to predict the actual loss of mass of steel at different current density levels have been confirmed in study .But the corrosion process follows the Faraday's law approximately³⁴. The law is expressed here as

$$M_{loss} = \frac{M.I_{corr}}{T}t$$

where, M_{loss} is the mass of consumed steel in gm; M is the atomic weight of Fe ion =56 g/mol, z is ionic valiancy =2.5 (Average value of valiancy of Fe²⁺ and Fe³⁺),F is Faraday's constant, =96,500 C/mol; I_{corr} = corrosion current and t =the corrosion time in seconds. The corrosion current density i_{corr} is defined as the corrosion current per unit steel surface area. If the unit length considered is equals to 1 cm and the unit of diameter d is in mm, a relation between I_{corr} in ampere (A) and i_{corr} (IA/cm²) can be obtained as given below:

$$I_{corr} = 1 \times \pi \frac{d}{10} \times i_{corr} \times 10^{-6} = 10^{-7} \times \pi di_{corr}$$
(8.a)

Mass loss / cm
$$M_{loss} = \frac{M10^{-7} \times \pi di_{corr.}}{z.F} t$$
 (8.b)
The rate of mass loss $\frac{dM_{loss}}{z.F}$ with the help of Faraday's law as

The rate of mass loss $\frac{dM_{loss}}{dt}$ with the help of Faraday's law as

$$\frac{dM_{loss}}{dt} = \frac{M i_{corr}}{zF} [mole / (m^2 s)]$$
(9)
The following simple equation to calculate rate of mass loss and rate of rust production per year³⁵

$$\frac{dM_{loss}}{dt} = 9.127 i_{corr} [kg / (m^2 year)]$$
(10)

If the diameter of a corroding bar is ϕ then the total mass of consumed steel per unit length of bar for a given period of active corrosion time t is given in Equ.11.

$$M_{loss} = 9.127 \pi \phi \int_0^t i_{corr} dt [kg / m]$$

The diffusion rate goes down as the iron ionic diffusion distance increases on thickening the rust layer and the rate of rust production decreases³⁵. From their experiments they proposed the formula below to calculate the rate of rust production with time:

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$$\frac{\mathrm{d}M_{\mathrm{r}}}{\mathrm{d}t} = \frac{\mathrm{k}_{\mathrm{p}}}{\mathrm{M}_{\mathrm{r}}} \rightarrow \mathrm{M}_{\mathrm{r}} = \left[2\int\mathrm{k}_{\mathrm{p}}\mathrm{d}t\right]^{1/2}[\mathrm{kg/m}] \tag{12}$$

Where, k_{p} is an empirical coefficient related to the rate of metal loss and is given as: $k_{\rm n} = k_{\rm coef} (1/r_{\rm m}) \pi \phi i_{\rm corr}$ (13)

 ϕ is expressed in m and I_{corr} in A/m², while k_{coef} is a coefficient that allows for the reduction of corrosion rate with rust thickness. The rate of rust production in relation to rust layer thickness is needed. Eq. 12 assumes that the rust layer formed is uniformly distributed and the diffusion properties are the same across the thickness of the rust layer. Examination of corroded bars embedded in concrete, under natural exposure, showed that the corrosion products form two layers. Although the composition of the two layers is found to depend on the environmental exposure in all cases, the inner layer was found to be denser than the outer. For layers of rust, with varying diffusion properties throughout the thickness, Faraday's law assume uniform rate of rust Production and gives unrealistic result. The relation was established as

 $M_{loss} = min(M_{SFL}.r_mM_{rIW} - M_{diff})[kg/m]$ (14) In which M_{sFL} is the steel mass consumed according to the Faraday law (Eq10), M _{r,LW} is the rust

produced²². M_{diff} is given as

 $M_{diff} = r_m M_{rIW} - M_{SFL} \qquad \text{for } r_m \frac{dM_{rIW}}{dt} < \frac{dM_{SFL}}{dt}$ (15) for $r_m \frac{dM_{rIW}}{dt} > \frac{dM_{SFL}}{dt}$ $M_{diff} = 0$

Where, $dM_{r,IW}/dt$ is the rate of rust productions according to Eq. 15 and dM_{SFL}/dt is the rate of consumed steel.

RESIDUAL TENSILE STRENGTH OF CORRODED REINFORCEMENT

Natural corrosion is very complicated, non-uniform and pitting type and behavior seems to be different than the artificially corroded steel. In present clause includes review of literature regarding the methods proposed by authors to calculate tensile strength of naturally as well as artificially corroded reinforcement.

The yield strength and modulus of elasticity of corroded bar are given as follows³⁶.

$f_{yx} =$	$\left(1-\frac{1.2+\Delta_{\rm W}}{100}\right)$	uniform corrosion	(16.a)
	1 98/		

f	$\frac{1}{vx} =$	(1	$-\frac{1.00\Delta_{\rm W}}{100}f_{\rm v}$	pitting corrosion	(16.b)
	ул	·	100 97		(/

Where, fy=yielding strength of non-corroded reinforcement; Δw =the corrosion mass loss percentage

$E_{sx} = (1 - \frac{100}{100})E_s$	uniform corrosion	(17.a)
$E_{sx} = (1 - \frac{1.13\Delta_w}{100})E_s$	Pitting corrosion	(17.b)

where, Es is the modulus of elasticity of non-corroded reinforcement.

Experiment has been carried out on corroded reinforcement in accelerated process embedded inside the concrete as well as bare bars³⁸. On the basis of linear statistical regression they suggested the residual strength of corroded bare reinforcement can be determined by using following generalized equation.

 $F=(1-0.01+\alpha Q_{corr}) F_o$ and $f=(1-\beta Q_{corr})f_o$

(18)

where α and β are force and strength factor, respectively, that represents the effect of local attack penetration on residual strength. Qcorr is the % of corrosion.F,F0 are yield or ultimate force of corroded and non corroded reinforcement, respectively, and f and f₀ are yield or ultimate strength of

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corroded and non corroded reinforcement, respectively. The relation between α and β ` are given as follows.

 $\beta = \alpha/(1-0.01 \text{ Q}_{corr}) = \alpha \text{ A}_{so}/\text{A}_{s}.$

(19)

A_{so} and A_s are initial and average cross sectional area, respectively. Sever is local attack, the value of α is higher and there is greater reduction in residual strength. If there is no local penetration attack, α =0. They advocate that above formulae can be used in practice with reasonable confidence. Equations 18 and 19 mainly depend on Q_{corr} and it can be determined using equation. Tensile strength of corroded bars from artificial corrosion and from natural corrosion collected from demolition of old structures corroded by carbonation^{39, 40}. They expressed the relation between ultimate strength and yield strength of corroded and non-corroded bars.

$$f_{yc} = \frac{\alpha_{yc}}{1-n_s} f_{yo}$$
 and $f_{uc} = \frac{\alpha_{uc}}{1-n_s} f_{uo}$, (20)

Where, n_s =degree of corrosion, f_{yc} and f_{uc} are yield and ultimate strength of corroded bars, and f_{yo} and f_{uo} are yield and ultimate strength of non-corroded bars

$$\alpha_{yc} = \frac{f_{yc}}{f_{yo}} = 1 - \beta_{yc} n_{s}$$
, and $\alpha_{uc} = \frac{f_{uc}}{f_{uo}} = 1 - \beta_{uc} n_{s}$, (21)

 β_{yc} and β_{uc} are regression constants for yield and ultimate loads respectively and values are found to be 1.1 and 1.12 for artificially corroded bars and 1.12 and 1.36 for naturally corroded bars, respectively.

CONCLUSIONS

The present study has summarized some monitoring methods and to utilize the monitoring result for calculation of mass loss, strength loss of reinforcement on corrosion. Therefore, following conclusions may be drawn.

1- Corrosion of the reinforcement cannot be detected during visual inspection unless there are corrosion cracks on concrete cover. Formation of cracks is the key indicator of end of service life. Corrosion can be indicated instrumentally before it become serious. To predict the corrosion corresponding mass and strength loss regular concrete health monitoring for reinforcement corrosion should be done.

2- Various corrosion monitoring methods have been developed and also being commercially used to estimate the corrosion status of the reinforcement. Few complete method have been proposed to utilize the corrosion monitoring data such as (I_{corr}) corrosion current, mass loss (M_L) etc to calculate strength loss in reinforcement and corresponding flexural strength loss as per current Indian standard.

3- Mass loss calculated as above can be utilized for calculation of residual strength of in situ reinforcing bars.

4-Further the residual strength of reinforcement in in situ concrete can be utilized for calculation of residual strength of RC member for integrity appraisal of existing RC structures.

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