State of the Art on Relation of Corrosion of Reinforcing Steel with Surface Crack Width in Corroded Reinforced Concrete Structural Elements

Dheeraj Kumar Singh*, Harish Chandra Arora, Rahul Kumar***

**Post Graduating Research Scholar, Department of Civil Engineering, Gautam Buddha University, Greater Noida, India*
***Principal Scientist, CSIR-CBRI, Roorkee, India*

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Abstract: There has been a massive construction of reinforced concrete (RC) buildings over the past 100 years throughout the globe. The liberty in design and construction with reinforced concrete and the ease and confidence with respect to its tailored strength and durability has made it the most versatile building material. Despite of many advantages of reinforced concrete, it has a serious drawback of its degradation due to corrosion of reinforcing steel in it. The degradation due to corrosion results in reduction of designed service life of RC structures and even become a serious threat to life and safety of occupants if not detected and intervened timely. The prediction of corrosion level in RC building elements is a very important aspect as proper repair and rehabilitation measures can be adopted timely to prevent sudden failure of buildings. Among the different forms of deterioration of constituents materials of RC structures, the concrete cracks formed on the concrete cover is a major one. The surface crack width on account of the corrosion of embedded steel has been attempted by various researchers for prediction of corrosion level through their experimental results and models generation. In the present paper a state-of-the-art report has been prepared based upon the outcome of some of the research studies. The results of these studies have been reported and discussed in terms of the relation of surface crack width on concrete with corrosion of embedded steel in RC structural elements.

Keywords: Corrosion, Crack width, RC elements

Introduction

The corrosion of reinforced concrete, due to its sensitive nature, is a condition that greatly affects the reliability and durability of reinforced concrete structures. Concrete provides reliable protection for reinforcement, but serious mistakes are possible. For example, it could be the wrong choice of concrete component, failure to build construction, unintended consequences of action, and an increase in aggression. So in terms of performance, the condition of the reinforcement and the quality of the concrete are factors that reduce resistance. Reinforcement structures must be resistant to corrosion in order to operate during life. Rust is an irreversible damage to the metal, which progresses from surface to surface due to chemical reactions.

Corrosion processes can be divided into two groups:

• In first there is change in mechanical properties of steel, corrosion occurs due to failure of the concrete cover,

• In the second group concrete affects the reinforcement of the chemically modified form. Concrete failure is caused by an increase in the production of corrosion (corrosion) due to carbonation (distribution of CO2 in concrete) or due to penetration of chloride ions Cl

Further deterioration in reinforcement with take place in various stages which have been clearly studied by Thoft-Christensen[11] which is based on Fick's law diffusion model of chloride in concrete and accordingly durability degradation of reinforcement due to corrosion with time is a six step process as listed below and proposed relation of reliability with time is shown in **Fig 1.**

1. Chloride penetration
2. Corrosion initiation
3. Corrosion evolution
4. Initiation cracking
5. Crack propagation
6. Spalling

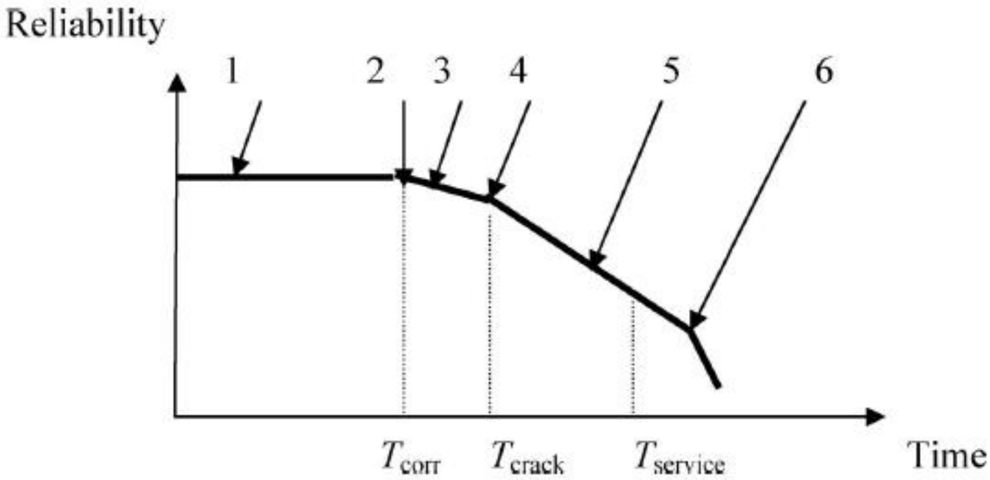


Fig 1 Deterioration with time

T_{Corr} the time for initiation of corrosion, T_{Crack} is time to initate of cracks and $T_{service}$ is service life of structure.

Comparing models with experiment results we found that Rodriguez model gives close results to experimental values when αvalues are between 4-8 but which value to be used is not clear. In Vidal's model crack width value is smaller than experimental values. While Zhang model gives larger crack values this model is suitable for low concrete cover. Stirrups are the first one to get corroded in RC Structural elements but still their no reliable and widely accepted analytical model available. Also, there is no analytical model with considers combined effects of stirrups and longitudinal rebars on cracks width propagation and generation due to its corrosion. Filipe mode is only valid for initial level of corrosion i.e., stage one or propagation level and fails to predict crack width in advance stages of corrosion. Bossio model is valid only when bi and be can be calculated manually at testing site or laboratory. Torres model is bit more useful to calculate crack with and reduction in residual capacity of beam due to corrosion. Andrade model was first model to implement effect of cover and rebar diameter in crack width study further this model was used in another paper [9]. Relation of crack propagation width with time was established to predict the corrosion values in future course. But due to difficulties in crack initiation and propagation prediction [8-13]. It is very difficult to predict accurate crack width with time

Protection of reinforced concrete structures against corrosion is provided by design principles such as concrete cover and concrete quality. Rust has a significant impact on the structure in terms of the final boundary condition and the performance limit. Therefore, rust not only reduces the reinforcing surface, thereby reducing resistance, but also increases the volume of the destructive product (corrosion), resulting in stiffness and pressure and cracks, which are undesirable during use.

The Process of Corrosion

Corrosion is an electrochemical process requiring an anode, a cathode and an electrolyte. The moisture present inside concrete behave as electrolyte while steel present behave as electrode and cathode. Current flows between cathode and anode. When steel becomes de- passivated in a region it is rendered anodic relative to the areas that remain protected. The reaction increases the metal volume Fe(steel) oxidizes to $Fe(OH)2$ and $Fe(OH)3$ and principates as $Fe2O3$ rust colour **.Fig 2**

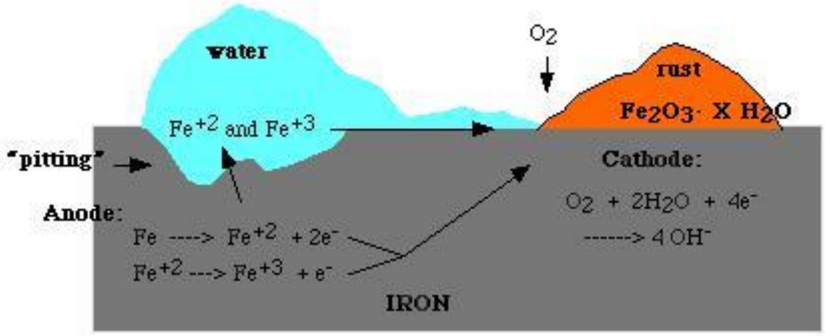


Fig 2 Corrosion process

The corrosion process RCC members is shown in **Fig 3**. When steel becomes de-passivated in a region it is rendered anodic relative to the areas that remain protected. Metal ions pass into solution in the electrolyte and the resulting excess of electrons are attracted to cathodic regions. Here they react with O_2 and water to produce OH^- ions. This transfer to anode where they associated with metal ions to form ferrous hydroxide which in presence of oxygen is rapidly concerted to rust. The important point to note is that the rate at which the reaction can occur is controlled by the availability of oxygen at cathode and anode. Hence, the progress of corrosion depends on the availability of O_2 not at the de-passivated region but in the sound concrete away from the crack and hence on the rate at which oxygen can diffuse through cover.

When rebar rusts, the corrosion products occupy considerably more volume than that of original steel. As a result, the corrosion products occupy considerably more volume than that of original steel corroded. This results the quite small reduction in cross sectional area of rebars. This volume expansion will produce internal stresses to cause cracking in concrete and then spalling of cover as result of stress relaxation. After cover spalling the rate of reinforcement increases up to 10 times sufficient to cause significant to cause significant weakening of the bars in a short time relative to design life of structure.

Initially the steel surrounded by fresh concrete will not be corroded due to alkaline nature of concrete, which renders the steel passive. With passage of time CO_2 from air reacts with hydroxide ions present in concrete, this phenomenon is called as **Carbonation** this reduced the alkalinity of concrete to such an extent that passivity of steel is ruin and corrosion process starts. **Fig 3**

A good concrete quality and cover can prevent carbonation penetration to reinforcement. In good quality concrete carbonation will be at estimated rate of 1mm/year. Hence adequate clear cover should be provided as per specified by various RCC codes. However, carbonation will not occur in underwater RC structure.

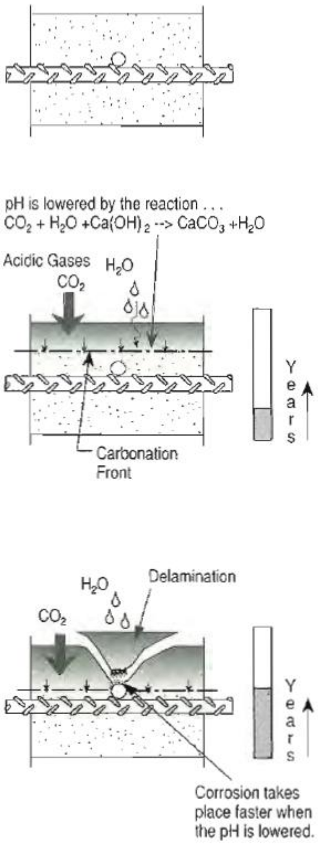


Fig 3 Carbonation Process

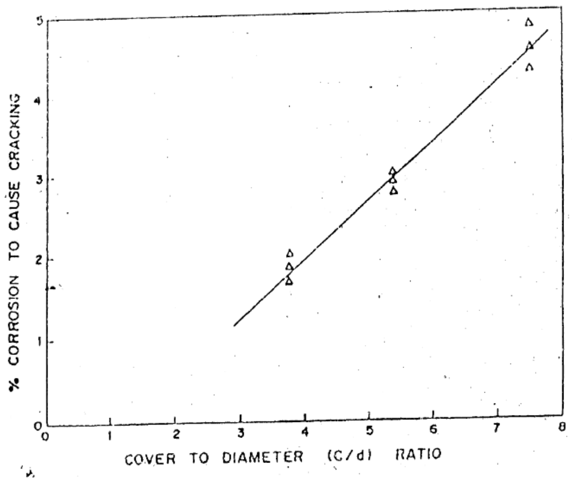
The presence of chlorine may be in water, aggragates or in admixtures used during constrcution process.Chlorine may also be introduced in structure from environment containg chlorine like sea water and it penetrates inside to reach steet.The contact of steel and chloride in existence of moisture and oxygen causes corrosion.As the rust layer buils stress are generated by volume expansion and cracks develops.

Crabonation and Chlorination depends uopn the following factors –

- Permiability of concrete
- Amount of moisture present
- Content fo chemical concentration coming in contact with concrete.

The parameters that are likely to influence the spalling of concrete ca be derived easily. The internal forces generated by corrosion will depend upon the depth of corrosion, bar diameter location. The ability of concrete to resist these forces depends on the cover to bar ratio (c/d) if this ratio is more than 3 than little significant damage occurs. During corrosion process high internal stresses (bursting forces) causing the cracking of concrete are due to increasing bar diameter initially due to corrosion, whereas the more thickness quality of concrete cover the more is the resistance to corrosive forces.

Figure 4 depicts the influence of the c/d ratio on the percentage of corrosion necessary to cause cracking. According to the statistics, the c/d ratio is a highly important corrosion prevention component. In a c/d ratio of 7, 4% corrosion initiates cracking, whereas in a c/d ratio of 3, only 1% corrosion is needed to commence cracking.



Amount of corrosion to initiate cracking versus c/d ratio.

Fig 4 Amount of corrosion to initiate cracking versus C/D ratio

Preventive Methods

Preventive measures can be applied place where construction is done in aggressive environment or where cover in structural element is less then prescribed limit. The main methods are:

- cathodic protection
- galvanized or stainless-steel reinforcement
- corrosion inhibitors
- concrete coatings

Analytical Models for Crack Width evaluation

Model 1

Andrade et al's model[1]

The present model established a relation between crack width of RC structural elements and corrosion rate. The experiments were performed on T beam and square column exposed atmosphere for 15 years. Crack width was measured on T beam 11 times on different dates and square column on 7 times. It accounted for 170 crack width readings in T beam and 90 readings for column. Based on analytical studies followings relations were evaluated.

$$Wmm = k(\frac{Px}{R})$$

$$Wmm = k(\frac{Px}{\frac{C}{\emptyset}})$$

$$Px = 0.0115 * Icorr * t$$

Wmm width of crack in mm

Px is pentation depth is concrete cover and Ø is the diameter of rebar

Models 2

Torres et al's model[2]

In this paper experiment is done on 12 beams of 100x150x1500 mm concrete beams reinforced longitudinally with one 10 mm diameter bar. NaCl is mixed with cement during concrete mixing. This introduced in beam help to induce corrosion Chloride ion concentration is 3% of the weight of cement. Water cement ratio is 0.5 Portland type 1 cement is used, coarse aggregate of 13 mm size is used.28 days cylinder compressive strength is 27MPa.Anodic current of 80μA/cm^2 for a number of days. To accelerate corrosion rate constant anodic current was given to 3 bars. Crack monitoring was performed with help of magnifying glass and crack comparator was used to measure crack width. After crack width examination beam was tested for bending. Average corrosion penetration xAVG was given by formula.

$$XAVG = \frac{\Delta Wgx10^3}{p * L * Ø}$$

Where p is density of steel, Ø rebar diameter and L is zone length of rebar. $\Delta Wg$is the gravimetric mass loss of steel before and after corrosion.

Various experimental relation is given. Relation between crack width CWmax and Xavg(average corrosion penetration).Xavg and maximum pit depth PITmax , relation between Residual load capacity RLCcor and Pmax maximum load registered during flexure test after corrosion.

$RLCcor = Pmax, corr/11.4$

$CWmax = 6.4 * Xavg/ro$

$PITmax = \alpha * Xavg$

Where α is between 3 to 10.

It was found that crack evolve more rapidly in dry environment rather than humid condition. Pit formation in wet condition also accelerated compared to dry conditions. Average radius loss and residual load capacity decrease 30-40% in humid conditions. If corrosion s highly localised residual shear capacity decrease about60% for similar average rebar radius loss. Flexure load capacity of beams decrease with formation of deep pits on rebar.

Model 3

Bossio et al's model[3]

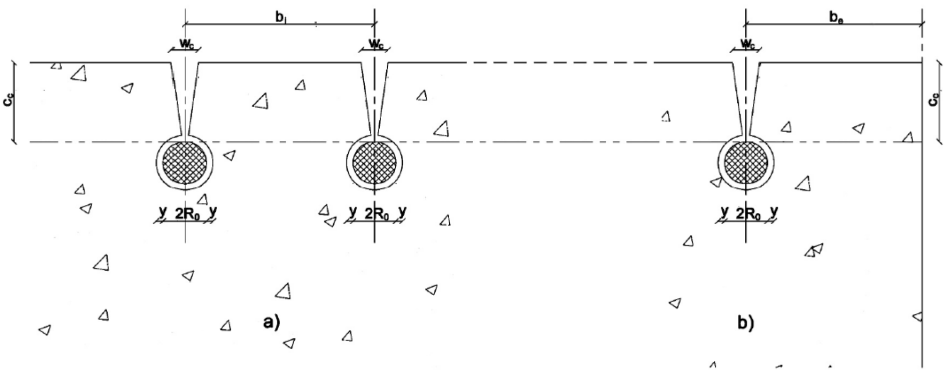
Authors here developed a model relating crack width in RC building with loss of steel cross-sectional area due to corrosion. Hence here authors tried to relate corrosion in steel with cracks developments and a model is prepared to relate these. During corrosion there is volumetric expansion in bars and these leads to crack in concrete cover. After studying 200 FEM analysis two most suitable models were developed one for external bars and other for internal bars. Here concrete is assumed to be elastic in both tension and compression. Steel and oxide deformation are neglected. Steel bars at perimeters are displacement to arouse oxide expansion and crack opening.

Internal bar model

100 FEM analyses were performed to obtain this relation. Three bar of radius 5 ,8 and 10 mm are used in this study while concrete cover of 10,30 and 50mm are considered. It was found that greater the diameter of bar higher will be the crack and vice-versa. The modal is given below

Wc/y=(0.37+0.013*Cc)*ln(bi)+1.5-0.12*Cc

Here Wc is crack width in mm,y is the oxide expansion ,Cc is clear cover ,be is the distance between two bars. **Fig 5**



geometric parameters of FEM analyses: a) internal bar, b) external bar

Fig. 5 Bossio FEM Model

External Bar Model

Same as the previous model here also 100 FEM analysis were performed for external reinforcement i.e. it is at end of edge of structural members. The range of '**be**' is taken from 35 to 130 mm. Clear cover value 'Cc'is less than 'be'the distance from centre of edge bar to the edge of structural member.

$$\frac{Wc}{y} = (34 + 3.6 * Cc) * Cc * be\hat{}(0.6 - 0.39 * \ln Cc)$$

Corrosion Penetration and Oxide Expansion

In this paper a modal is developed to related these two effects. Ultimately crack width is also related to corrosion penetration by help of volumetric expansion of coefficient.

x=y/(0.95*n-1)

n is volumetric expansion coefficient

x is corrosion penetration rate; y is bar expansion.

The value of X and y can be directly evaluated design charts given in paper.

This model is based on measurement of be and bi values. Various analytical model is proposed in this study between crack width, corroded structures and corrosion penetration using FEM analysis. Measurement of crack width distance from free edge and distance between bars are important support of these models. Most difficult is to get the actual bar size in old building. Maximum deviation of 30% is considerably acceptable. Further onsite validation of parameters is necessary and should be taken carefully to get precise results.

Model-4

Rodriguez et al's model[4]

He gave model based on accelerated corrosion results and gave various equations to relate corrosion with crack width. He studied the effect of corrosion on reinforcement, concrete cover cracking and bond deterioration.

$$\emptyset = \emptyset^{\circ} - x$$

$$\tilde{W} = 0.05 + ß\,(X\text{-}X')$$

$$X' = 7.53 + 9.32$$

$$* c/\emptyset'$$

$X = \emptyset\left[1 - \sqrt{1 - \Delta As/As}\right]$ *1000/α

Where W is crack width in mm , Ø° is original diameter, Ø is corroded diameter, x is pit penetration, ∝ is attack penetration parameter, c is clear cover, X is attack penetration, X' is threshold attack penetration value , ΔAs is steel cross-section loss and As is sound steel cross -section.

Model-5

Vidal et al's model[5]

Here 36 beams were stored in chloride environment for 12 years under loading. Beams were taken into 2 sets A and B clear cover of beam A is 40mm and Beam B is 10 mm He gave model based on accelerated corrosion results and gave various equations to relate corrosion with crack width. He gave equations to relate corrosion and crack width relations.

∇Aso =As[1-[1-$\alpha/\emptyset'(7.53 + 9.32 * \frac{c}{\emptyset'})/1000]$^2]

w=K($\nabla As -$ ∇Aso)

W is crack width in mm, k is constant, Ø° is original diameter, Ø is corroded diameter, ∝ is attack penetration parameter, c is clear cover, ΔAso stell cross section loss for crack ignition and as is sound steel cross -section.

Model-6

Zhang et al's model[6]

The evolution of the corrosion pattern caused by chloride is initially examined in this study using cracking maps and true corrosion distributions along reinforcements set of two corroded beams, that had been exposed to a chloride environment for 14 and 23 years, respectively. The beams dimensions are (300×28×15 cm) the clear cover for first set of beams is 40 mm and for second sets is 10 mm.

$\mathrm{w} = 0.1916\nabla Asm + 0.164$

w is the crack width in mm and ∇Asm is average cross-section loss between two stirrups.

Model-7

Zhang et al's Modified model

This model is modified model of Zhang model here effect of concrete cover and diameter of rebars are included in study and it was found that considering these factors in Zhang model gives very accurate results.

$$\mathrm{w} = 0.1916\nabla Asm * (\emptyset/c) + 0.164$$

Where w is crack width in mm, Ø is corroded diameter, ∇Asm is average cross-section loss between two stirrups.

Model 8

Filipe Pedrosa et al's model[7]

This for First level of corrosion and crack width up to 0. 3mm.In experimental setup 11 RC beams of dimension 1500x1500x5000mm each beam was reinforced with a single corrugated steel bar. And the following equations were established.

W is crack width in mm, Px is corrosion penetration, β is corrosion attack penetration

Px=0.0116*Icorr*t

w
$= \beta * \mathrm{Px}$

$\beta = \alpha * Icorr^{-k}$

$w(t) = \alpha * \tau * t * Icor^{(1-K)}$

The experimental results show us width of crack is different for different level of corrosion and for 1 stage corrosion evolution of cracks is very rapid.

Model 9

E. Chen et al's model[10]

E.Chen and team[10] did research on 66 rebar extracted from cracked and pre-cracked RCC and FRC(Fibre reinforced beams) corroded for artificially for 3 years and give linear analytical models found out that there is no relation between the maximum flexural crack width and corrosion level. Pitting corrosion doesn't always induce longitudinal cracks in many cases severe pitting corrosion cases didn't initiate any longitudinal cracks. So, it is very hard to find a relation between crack width and rebar corrosion

$$\mu max = \frac{Aomin - Acmin}{Aomin}$$

$$Xuavg = do/2(1-\sqrt{1-\mu max})$$

μmax is maximum local corrosion level, $Xuavg$ is average pitting depth, do is initial diameter of rebar. Acmin is uncorroded section of rebar and Aomin is corroded area of rebar.

Model 10

Thoft-Christesen et al's model[12]

In this study 2-D and 3-D FEM modelling is done for RC beam is done for corrosion analysis and FEM is based on the experimental results suggesting the relation that crack width is directional proportional to rebar diameter. Here entire focus was on evaluating Υ which is called as crack-corrosion index and it is evaluated using FEM and finally and analytical linear equation is proposed. In case of multiple cracks located in adjacent rebars this model can be applied provided that spacing between rebars should not be grater than thrice the diameter of rebar.

$$\Delta Wcrack = \Upsilon \Delta Dbar$$

$$\Upsilon = 1.36(\alpha - 1)$$

Υ is crack corrosion index, ΔW is crack width and $\Delta Dbar$ is reduction in rebar diameter.

Model 11

Kuntal et al's model[13]

In this study a new latest approach to evaluate corrosion in reinforcement is established by observing surface crack, with the help of stimulation techniques MPC-RBSM (Model Predictive Control-Rigid Body Spring Models). Results from these stimulation techniques have been validated with laboratory experimental results on corroded beams with help of 3-D scanning technique. The accuracy of these models depends on various parameters further work on theses limitation is to be done by authors.

$$Ce = n\delta ie$$

Whereas Ce is estimated level of corrosion i.e. ratio of area loss to original area, δie is the estimated internal expansion(mm) and n is calibration constant.

Conclusion

In this state-of-art paper we tried to include almost all the analytical model established to relate crack-width with corrosion so that further hassle-free literature on present research topic. As a result, we've presented and discussed some experimental work on corrosion-induced crack prediction. The corrosion state is often described in terms of corrosion penetration or cross-sectional area loss, with a relation to crack opening, and it has been proven that literature models, all of which are empirical in nature, provide significantly varied findings. Numerous FEM and experimental analyses have yielded these results, which link the of superficial crack width to radial expansion of oxides, and then radial expansion of oxides to bar sectional-area loss. By measuring exterior crack width calculation of the value of bar section lost due to corrosion and the residual value of the load-bearing capacity of structural components can be calculated with NDT tools. No relationship is between transverse crack and corrosion, similarly stirrup corrosion. Although stirrups are the first one to get corroded and initiate cracking in RC member. It is very difficult to predict accurate crack width with time and hence no well accepted analytical model is developed for it till now. Cracking depends on cover of RC elements and diameter of rebars and various model in present study includes these factors in numerical models. Out of 3d-scanning technique and gravimetrical mass loss technique for measurement of rebar corrosion 3D scanning technique is most accurate method. Now a days it is used in all related research work.

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