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論 文

[1149] RC構造物の鉄筋腐食に関する一考察

A FRESH LOOK AT THE PROBLEM OF STEEL CORROSION IN RC STRUCTURES

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1. INTRODUCTION

Several papers have been published dealing with the mechanism of reinforcement corrosion in concrete, the factors associated with the problem and it's implications (1-3). However as more light has been thrown on the deterioration process, it seems that different factors play roles of varying importance in the different stages of the corrosion process. An attempt has been made in this paper to put forward an overall picture of the corrosion and deterioration process along with the roles and relative importance of the various key factors. The provisions in some of the international specifications dealing with concrete design are also discussed.

2. MECHANISM OF REBAR CORROSION IN CONCRETE

Reinforcement corrosion is an electro-chemical process that leads to the conversion of iron to it's oxides and hydroxides, in the presence of oxygen and water. The process involves the formation of micro/macro cells between the anodes and cathodes of which, "corrosion currents" are set up. The basic reactions at the anode and the cathode are as follows:

Anode: $Fe \longrightarrow Fe^{++} + 2e^{-} \longrightarrow Fe(OH)_2,\ Fe(OH)_3,$ etc..

Cathode: $O_2 + 2H_2O + 4e^{-} \longrightarrow 4OH^{-}$

The thermodynamics, etc. of the process are covered in literature in detail(4).

Normally, the high pH within the concrete (as a result of hydration of cement and presence of calcium hydroxide) protects the steel from corroding by formation of the gamma Fe_2O_3 film on the surface. However, if this passivating oxide layer is damaged due to reasons such as chloride attack, or the decrease in pH in the neighbourhood (e.g. by carbonation), the steel becomes potentially "active" and the corrosion can be initiated provided other conditions such as the availability of oxygen, moisture,

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etc. for the cathodic reaction above are met. Further, the corrosion products are more voluminous than the parent metal and hence as the corrosion proceeds, they exert a "bursting pressure" on the surrounding cover concrete which results in cracks being formed along the reinforcing bars.

3. FACTORS AND STAGES IN REBAR CORROSION IN CONCRETE

3.1 Factors

Different factors hold the key to the initiation and propagation of corrosion in the steel embedded in concrete. For example, the chloride ingress, which in turn depends upon water-cement ratio, etc. (5), may determine the point of initiation of corrosion, but it could largely be the oxygen availability, that controls the corrosion rate from that point on. However, as Gjorv (6) and Shuttoh (7) have reported, it is not so much the quality of concrete, as such, but factors as the moisture content of the matrix, that hold the key to the amount of oxygen diffusion. In addition to water-cement ratio and the cover thickness, limits have also been set on permissible crack widths in structures (8), to make it difficult for the deleterious matter to reach the reinforcing bars.

3.2 Stages

Based on the brief outline given above, of the corrosion process and the factors affecting it, the deterioration due to rebar corrosion in concrete can be divided into several stages. Table 1 lists the factors that influence the deterioration at the various stages. It should be remembered, however, that this compartmentalization is not water-tight and the influencing factors also are inter-related and inter-dependent.

Table 1: Stages and Factors in the Corrosion Process

Stage	Phenomenon	Main Influencing Factors
I	Chloride penetration and build-up	1. Water-cement ratio 2. Pore size distribution 3. Amount of water in pores 4. Cover thickness
II	Initiation and propagation of corrosion	1. Continued O_2 availability 2. Concrete moisture content 3. Characteristics of steel 4. Cathode:anode area ratio
III	Cracking along and between bars	1. Concrete strength 2. Cover thickness 3. Diameter of steel bars 4. Spacing of bars
IV	Spalling	1. Extent of cracking 2. Cover thickness

From the table above, it can inferred that, though the first stage is relatively harmless from the structural standpoint, the behaviour of RC members could under-go definite changes once the cracks are formed along the reinforcing bars (stage III). It has been reported (2,3) that rebar corrosion (to the extent of longitudinal crack formation) leads to substantial reduction in the ductility and the load carrying mechanism of RC beams and columns. The data to clearly understand the structural implications of the intermediate degrees of corrosion is unfortunately lacking. However it would be over-pessimistic to base the service life computation on the basis of the chloride concentration reaching a threshold value at the level of the reinforcing bars. At the same time, the cracks formed along the reinforcing bars (10), deserve special attention, as they are not normally accounted for in the design stage.

A clear understanding of the stages of deterioration also helps in proper diagnosis and treatment of actually deteriorated structures. For example, one of the ways to control the corrosion in an structure would be to try and control the oxygen supply, even if the structure has excess chloride concentration.

4. PRESENT PHILOSOPHY IN DESIGN

The present philosophy in design of concrete structures is based upon the available information on the corrosion process and the factors affecting it. Table 2 summarizes the requirements of a few of the codes of practice dealing with the design of concrete structures (8) developed in different countries.

Table 2: Design criteria for concrete structures

Code / Parameter	(1)	(2)	(3)	(4)	(5)
w:c (%)	-	50	45	45	-
Strength[a] (MPa)	-	-	40	44	-
Cement (kg/m^3)	-	300	400 and less than 500	400-450 and less than 500	-
Cover[b] (mm)	Max(30, 1.25xDmax 1.25xGmax)	Max(35, Gmax+5)	75	70	50
Crack width (mm)	0.1 and 0.2 for worst load	0.1 at steel level	0.3 and (.004xCover) over main bar	steel stress less than 100 MPa	0.33

Notes:

1. Codes 1-5 above refer to (1) Comite European du Beton, 1970 (2) New CEB approach, 1976 (3) FIP recommendations for the design of concrete

sea structures (4) DNV rules for offshore structures (5) ACI : Building code 1972
2. "a" refers to cube strengths
3. "b", the Dmax and Gmax refer to the maximum size of the bar and the aggregate respectively
4. Some of the specifications also prescribe the formulae for computation of parameters like the crack width, spacing, etc..

Comments
1. Though a direct comparison between the various codes is difficult to make, it should be noted that the approach adopted in the various codes is quite different, with the permissible covers ranging from 35 to 75mm and the crack width from 0.1 to 0.33mm.
2. Some of the important considerations not accounted for in these provisions include the spacing between bars (3), and the possibility of the formation of macro-cells due to diverse factors like different exposure conditions, concentration differentials, etc..

5. ALTERNATIVE APPROACH

Figure 1 is a qualitative representation of deterioration due to rebar corrosion. The deterioration process is divided into two stages, the "activation" (I) of the bars and the "propagation"(II) of corrosion. The factors that have an effect in these stages have already been listed above (Table1).

Based upon the assumption that the limiting amount of permissible corrosion is that which leads to formation of longitudinal cracks along the reinforcing bars, an alternative approach to design in the case of structures susceptible to rebar corrosion is suggested in Fig. 2.

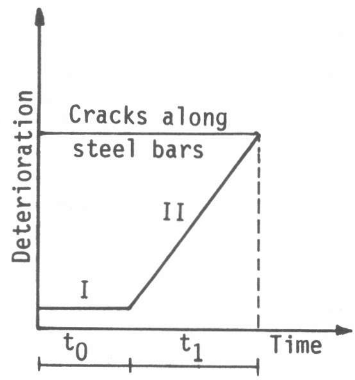
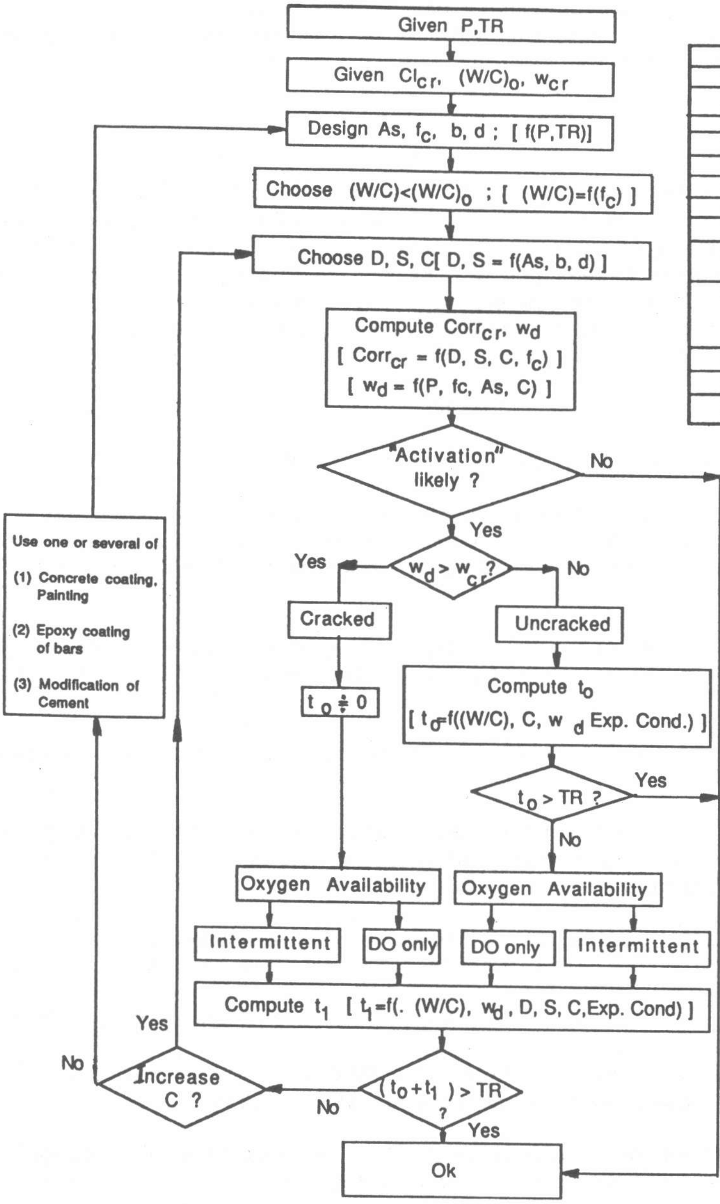


Fig.1 Deterioration vs. time

In the "activation" stage, chloride ingress occurs under submerged conditions or due to cyclic exposure to sea water. Assuming that the steel becomes active after the chloride ion concentration in the neighbourhood exceeds a known critical level, the t_0 can be estimated, depending upon the exposure conditions.

Then, once we know the cover thickness and the tensile strength of the concrete, we can compute the required internal pressure to cause cracking. This in turn should give the thickness of the layer of the corrosion products necessary, depending upon the diameter of the bars and their spacing. Based on the amount of oxygen required to oxidise unit quantity of iron, the total oxygen requirement can be worked out. Making justifiable assumptions about the diffusion of oxygen, the t_1 can be determined.

Further, the presence of cracks is likely to have a substantial effect on the influx of oxygen and chloride ions into the matrix, especially if it is subjected to cyclic submersion in sea. Bazant (9) has reported, that cracks 0.1mm wide, spaced at 70mm, caused a 2.25 times increase in the drying permeability of reinforced concrete specimens.



P	Load
TR	Required life
$(W/C)_o$	Critical W/C
As	Area of steel
w_{cr}	Critical crack width
f_c	Concrete strength
b,d	Section size
D	Diameter of steel
S	Spacing of steel
Cl_{cr}	Cl^- conc. to "Activate" steel
$Corr_{cr}$	Critical corr. to cause cracks at surf. or bet. adj. bars
W_d	Crack width
DO	Dissolved Oxygen
t_o, t_1	See Fig.1

Fig.2 Service life of corrosion prone RC structure

Limitations: The approach presented here is applicable only to cases of general corrosion and does not address the cases where, longitudinal cracks are not formed even though there may be considerable damage because of reinforcement corrosion. Such cases include, pitting corrosion, provision of excess cover thickness, etc..

6. CONCLUSIONS

This paper discusses the role and importance of the various factors in the deterioration of concrete structures by reinforcement corrosion, and lists the provisions of some of the codes of practice. Also an alternative approach to design based upon a rational formulation of the mechanism is presented. Considerable amount of work, however, needs to be done to quantitatively estimate the various parameters presented here.

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