Probabilistic Model for Assessing Chloride Threshold for Variable bar Lengths in Reinforcement Corrosion

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ABSTRACT

The focus of this study is on assessment of acceptable thresholds for chlorides (or failure probability) appropriate to the length of exposed structural member, from recommended threshold. It is commonly known that chlorides in exposed concrete induce corrosion (or pitting) in rebar. However, to initiate the corrosion process at the rebar surface, the content of chlorides has to exceed a certain threshold value. A plethora of environmental factors (micro and macro-climatic) can trigger the initiation of chloride-induced corrosion in rebar that a single, globally accepted threshold value for chlorides with general applicability, does not exist. Nevertheless, research has recommended several thresholds for the onset of corrosion in different exposure environment. The acceptable threshold for chlorides can be described from the recommended via a statistical transform, by treating it as a size-dependent statistical phenomenon, for which theory of probabilistic reliability applies. This is because corroding spots on any surface of steel reinforcement and carbonated concrete are randomly distributed and appear to depend on the size of member. Therefore, it is suggested that the acceptable threshold for corrosion initiation, in reinforcing bar lying within carbonated concrete, be assessed statistically against a measurable structural length rather than service environment.

Keywords: *Acceptable threshold value, characteristic length of rebar, acceptability coefficient*

INTRODUCTION

In recent years, the accent has been on performance based design of reinforced concrete structure vis-à-vis assessments using theory of structural reliability, failure probability and service life modeling along with deterministic durability checks and stochastic analyses of time-dependent carbonation, resistance to chloride ingress and corrosion, etc. (Folic, 2009). And it is commonly known that chlorides in exposed concrete structure induce corrosion (or pitting) in rebar. However, the onset of corrosion at the rebar surface requires that the content of chlorides within concrete has to exceed a certain threshold value. But, a plethora of environmental factors (micro and macro-climatic) is known to trigger the initiation of chloride-induced corrosion in rebar that a single, globally accepted threshold value with general applicability, does not exist. In this regard, researches have recommended several thresholds for the onset of chlorides-induced corrosion in different exposure environment. The fact that recommended thresholds of chlorides in reinforcement corrosion appears to depend on the structural length of member from which it is obtained, raises fundamental questions regarding the reliability of these values for use in service life modeling (Angst, 2011). This is because, it cannot be very correct to use the same recommended threshold value on a relatively shorter laboratory specimen as well as for service life models of life-size reinforced concrete. It is to be expected that recommended threshold of chlorides established on a relatively smaller laboratory specimen, cannot with reliability be used for service life modeling of life-size reinforced concrete structures, without modification.

Therefore, acceptable threshold rather than recommended threshold, better describes the onset of corrosion in exposed structural concrete. Incidentally, the acceptable threshold value can be described from the recommended via a statistical transform, by treating the recommended threshold as a size-dependent statistical phenomenon, for which theory of probabilistic reliability applies. This fact that any corroding spot on the surface of steel reinforcement and carbonated concrete are randomly distributed is enough justification to apply statistics. And the number of corroding spots appears to depend on the size of member. It is suggested that the acceptable threshold for chlorides required for corrosion initiation, in reinforcing bar, be assessed statistically against a measurable structural length rather than service environment. The above assertion stands confirmed in Angst (2011), who shows that threshold value for chloride-induced corrosion can occur anywhere across the entire length of a specimen, therefore, the probability of corrosion in the reinforcing steel of concrete, must indeed be dependent on the rebar length (or constructive size of the member) rather than service environment.

It is only reasonable to suggest that the length of a concrete structural member ought to be taken into account, in order to derive the acceptable threshold for chlorides. Therefore, this study focuses on the issue of assessment for acceptable threshold for chlorides (or failure probability) that is appropriate to each length of exposed structural member.

Since the onset of induced-corrosion equals the threshold value for corrosion initiation (or the percentage of chloride by mass of cement-binder at which corrosion is initiated). This idea of a two-stage deterioration stems from the simplified service life prediction (SLP) model established by Tuutti (1980; 1982). Since the end of service life is assumed to coincide with the destruction of inherent passivity of reinforcing steel, whatever the specified threshold value therefore, becomes a critical parameter $\mathbf{C}_{crit}$ in calculating resulting service life. Nevertheless, literature review by Glass, Hassanein and Buenfeld (1997) reveal that the recommended threshold values, measured from structures at corrosion initiation, ranged from 0.17 - 2.5%wt. of cement.

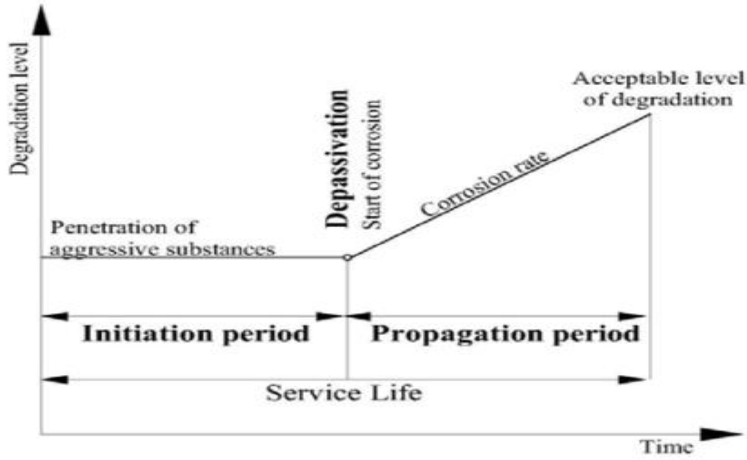

Figure 1.1: Simplified service life prediction model (Tuutti, 1980)

In the absence of carbonation, the probability for corrosion initiation has been found to be less than 40% when the chloride content is less than 0.4% weight of cement (DuraCrete, 1998). This is because, corrosion risk at a chloride content of 0.4% weight of cement is assumed to range from low to negligible (Broomfield, 2007; Polder, 2009). Moreover, when carbonation front approaches steel reinforcement, then corrosion initiation can occur at the lower threshold value (Ballim, Alexander and Beushausen, 2009; Glass and Buenfeld, 1995). The fact in table 1, however, is confirmation that interaction of chloride ions and carbonation speeds up the destruction of the passive layer surrounding reinforcing bars even as carbonation reduces the pH of concrete. Such that a lower pH of concrete is more conducive for corrosion occurring. For example, table 1 below shows clearly that the degree of carbonation close to rebar of carbonated concrete is relevant to the appearance or otherwise of reinforcement corrosion.

Table1: Relationship between Ph and state of reinforcement corrosion

pH	**State of reinforcement corrosion**
Below 9.5	Commencement of steel corrosion
At 8.0	Passive film on the steel surface disappears
Below 7	Catastrophic corrosion occurs

Source: Sobhani and Ramezaninpour (2010)

Since the pH of concrete varies depending on composition of concrete, type of cement and w/c ratio of concrete. It follows from the foregoing that a fixed value for chloride risk cannot be readily expected.

Moreover, the chloride threshold also varies with cracks in the concrete because openings due to cracks provide a quicker path to the reinforcement (DuraCrete, 1998). Conversely, if the pores are saturated, then, the oxygen availability will be low and corrosion initiation will be delayed (Bertolini, 2008). So, it is difficult to establish a precise value of chloride content below which corrosion does not occur (table 2), since chloride threshold depends on several parameters (Hope and Alan, 1987).

Table 2: Corrosion risk in concrete containing chlorides

Total chloride (wt. % of cement)	**Condition of concrete adjacent to reinforcement**	**Corrosion risk**
	Carbonated	High
Less than 0.4%	Uncarbonated, made with cement containing less than 8% C_3A	Moderate
	Uncarbonated, made with cement containing 8% or more C_3A	Low
	As above	High
0.4%-1.0%	As above	High
	As above	Moderate
More than 1.0%	All cases	High

Source: Hope and Alan (1987)

Statistical Link between Threshold and Rebar Length

This study is aimed at advancing a probabilistic model that distinguishes the range of specimen lengths applicable to a particular chlorides threshold and the coefficient of acceptability of chlorides threshold applicable to other lengths of rebar. The concept of a chloride threshold value should be understood as an increase in corrosion probability occurring after the particular value is exceeded. This leads to expression of the chloride threshold as a statistical distribution. Again, since weak spots on the surface of the steel rebar and in the cement matrix are randomly distributed, the initiation of corrosion process can be treated as a statistical phenomenon using table 3.

Probabilistic Service Life Modeling of Structural Concrete

In probabilistic service life calculation, the term failure probability is comparable with target probability, $P_{(target)}$ (Foliæ, 2009). In the example shown in Fig. 4.

Let the action (or load) stochastic variable '*S*' describe the tensile forces while *'R'* describe the resistance (or strength) where *S, R* denote the variable functions of a cross section located within the characteristic length such that the tensile resistance *R,* is always higher than ***S*** or load (Kraker, de Tichler and Vrouwender, 1982). Let the conventional probabilistic factor of safety ($^R/_S$) or utilization ratio be established as:

$$^{S}/_{R} = 0.9 \qquad (2.1)$$

Thus, a tolerable corrosion of 1 out of 10 bars (or 10%) of tension steel bars located bottom of the cross section that is depicted in Fig. 1.4b and the service life of this structural member is considered reached as soon as 1 out of 10 bottom bars begin to corrode. This implies also that when performing experiments with reinforcing bars of the same characteristic length *L*, the threshold value for chlorides C_{crit} relevant to this service life model is the one at which 10% of the test samples experiences corrosion onset. Thus, for the cross section shown in Fig. 1.4b, the tolerable or acceptable probability of corrosion in rebar within any characteristic length becomes:

$$P_{(target)} = 10\% \qquad (2.2)$$

Table 3: Set of Operational Limit States with the reliability index.

Limit State	Event	Reliability Index β_0
SLS	Onset of corrosion	1.5 – 1.8 (EC 1, NEN 6700, respectively)
SLS	Corrosion induced spalling and corresponding failure in water tightness	2.0 – 3.0 Proposal
ULS	Collapse of the structure	3.6 – 3.8 (NEN 6700, EC 1, respectively)

Source: Siemes and Rostam (1990); Schiessl, *et al.* (2004).

Reliability Calculations

Now consider a static system in Fig. 1.4(a) and (b), where the load-bearing capacity of the system is compromised at three different points, indicated by A, B, and C which in effect are assumed to represent three different levels of control of local corrosion onset within a rebar length L. The characteristic length of rebar should be the length relevant to a particular threshold to be used in probabilistic modeling for corrosion initiation and for prediction of the service life of that concrete structure. However, for purposes of this analysis, the characteristic length L will be defined as the length, within which the initiation of one pit even if it occurs in one bar becomes critical regardless of its location along the rebar.

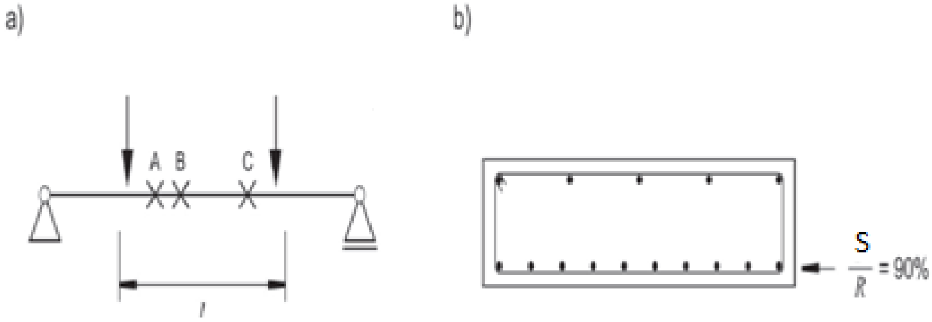

Figure 4: Schematics of a static system compromised at points A, B and C.

Considering 3 levels of variance (or coefficient of variation) of the relevant length, the recommended threshold does not have to exceed its mean value except by a factor of its standard deviation, as in equation below:

$$\overline{C}_C = C_{crit} + \beta.\delta \qquad (2.3)$$

Where: $\mathbf{C_{crit}}$ is recommended threshold for chlorides.
In the warm and humid clime where carbonation of concrete is often associated with chlorides penetration $\mathbf{C}_{crit}$ can be as low as 0.17%wt. of cement (Ballim *et al.,* 2009; Glass and Buenfeld, 1995).

$\overline{\mathbf{Cc}}$ is the statistical mean of chloride threshold.

β is the accepted reliability index corresponding to the on-set of corrosion within serviceability limit state of structure(or the constant that comply with the necessity that only 10% of the test result must fall below the expected).

From table 3, $\beta = \frac{[1.5 + 1.8]}{2} = 1.65$

δ is the standard deviation for chloride threshold. In humid or frequently changing conditions, for example, a standard deviation of 0.1 (for $^w/_b$ = 0.40 to 0.50) and 0.15 for w/b = 0.30 applies (Schiessl and Lay, 2005).

In the warm and humid clime, by Substituting the value of and $\mathbf{C_{crit}}$ in equation (2.3), the mean value of threshold for chlorides in concrete of variable $^w/_c$ ratios can be obtained thus:

For $^w/_b$ = 0.4 to 0.5,

$$\overline{C_C} = C_{crit} + 0.165 = 0.17 + 0.165 = 0.34 \qquad (2.4)$$

For $^w/_b$ = 0.3,

$$\overline{\mathbf{Cc}} = C_{crit} + 0.247 = 0.17 + 0.247 = 0.42 \qquad (2.5)$$

Characterizing the Relevant Length of Rebar

Then, let **V** stand for the statistical variance (coefficient of variation) of the relevant length of rebar. However, the length of rebar relevant to a particular chloride threshold, in fig 1.4, could be calculated statistically by an inverse function of the variance **V**, which is relatively small for point A and relatively large for point C. And the characteristic length **L** of rebar relevant to a particular chloride threshold could thus be found, using the equations as below:

$$L = K_f^2 \frac{\overline{C_C}}{\delta} \qquad (2.6)$$

$$V = \frac{\delta}{[K_f C_C]} \qquad (2.7)$$

$\mathbf{k_f}$ **-** target multiplier corresponding to each level of variance for the relevant length of rebar, assuming that the reliability index â is both constant and less than two $[\beta \leq 2]$.

It follows that the target multiplier $\mathbf{k_f}$ = 0.85 at point A, or 1.00 at point B, and 1.22 at point C.

V – statistical variance (coefficient of variation) of the relevant length of rebar.

For $^w/_b$ = 0.4 to 0.5, and for $^w/_b$ = 0.3, the 3 levels of variance are statistically given at point A is as $\frac{V_B}{2}$; at point B as $\frac{2V_B}{2}$ and at point C as $\frac{3V_B}{2}$ respectively.

L - is the characteristic length relevant to a particular acceptable chloride threshold.

Hence, the statistical variance (coefficient of variation) **V** of the relevant length of rebar and of course the characteristic length **L** of rebar relevant to a particular acceptable chloride threshold are in table 4.

Table 4: Calculated variance **V** and corresponding characteristic length **L** of rebar

Statistical Parameters				Statistical Variance **V**	Characteristic length of rebar **L** [m]
w/b= 0.4-0.5	**δ** = 0.1	Point A	$\mathbf{K_f}$ =0.85	0.15	≥ 5.7
		Point B	$\mathbf{K_f}$ =1.0	0.3 = V_B	2.8 - 5.6
		Point C	$\mathbf{K_f}$ =1.22	0.45	≤ 2.7
w/b = 0.3	**δ** = 0.15	Point A	$\mathbf{K_f}$ =0.85	0.18	≥ 4.7
		Point B	$\mathbf{K_f}$ =1.0	0.36 = V_B	2.2 – 4.6
		Point C	$\mathbf{K_f}$ =1.22	0.54	≥ 2.3

Source: Experimentation, 2016

Acceptable Threshold of Chlorides and Coefficient of Acceptability

Recalling from equation (2.3) where recommended threshold chloride $\mathbf{C_{crit}}$ is given, the acceptable Chloride threshold $\mathbf{C_{crit,acc}}$ can be calculated as follows**:**

$$C_{rit,acc} = \left[C_{crit} + \beta.\delta\right]K_f - \beta.\delta \qquad (2.8)$$

And the acceptability coefficient "α" as:

$$\alpha = \frac{C_{rit,acc}}{C_{crit}} \qquad (2.9)$$

Where: $\mathbf{C_{crit}}$ is the recommended threshold for chlorides.

For the warm and humid clime for example, the acceptability coefficient of threshold can be calculated when ($^w/_b$ = 0.4 to 0.5) and for when ($^w/_b$ = 0.3) using equation (2.9).

The calculated values of characteristic length of rebar relevant to the particular acceptable threshold and the acceptability coefficient are entered in table 5.

Table 5: Calculated values of characteristic length of rebar and corresponding acceptable chloride threshold for reinforced concrete exposed to chlorides in the warm and humid clime.

	$^{w}/_{b}$ = 0.4 to 0.5			**$^{w}/_{b}$ = 0.3**		
	Characteristic length of bar			Characteristic length of bar		
	A	B	C	A	B	C
Characteristic length of rebar ***L,*** [m].	≥ 5.7	2.8 - 5.6	≤ 2.7	≥ 4.7	2.4 – 4.6	≤ 2.3
Acceptable threshold **$C_{crit,\ acc}$**	0.12	0.17	0.24	0.10	0.17	0.26
Coefficient of acceptability of threshold $\alpha = \frac{C_{rit,acc}}{C_{crit}}$	0.7	1.0	1.4	0.6	1.0	1.5

For reinforced concrete exposed to chlorides in the warm and humid clime, recommended threshold value for chlorides could be equal to acceptable value and used with real-life sizes of reinforced concrete component in the range of 2.4 - 4.6m when $^{w}/_{b}$ = 0.3 (or in the range of 2.8 - 5.6m when $^{w}/_{b}$ = 0.4 to 0.5). The calculated result in tables 1.5 show that for the characteristic length of rebar greater than 5.7m or lesser than 2.7m, when $^{w}/_{b}$ = 0.4 to 0.5, the acceptability coefficient of threshold is 0.7 lesser or 1.4 greater than the recommended threshold respectively. On the other hand, for characteristic length of rebar greater than 4.7m or less than 2.3m when w/b is 0.3, the acceptability coefficient of threshold is 0.6 lesser or 1.5 greater than the recommended threshold respectively.

CONCLUSION

In the warm and humid clime where carbonation of concrete is often associated with chlorides penetration, the following conclusions could be reached:

i. That recommended thresholds of chlorides established on relatively smaller laboratory specimen, cannot with reliability be used for service life modeling of life-size reinforced concrete structures without modification except for characteristic lengths of rebar in the range of 2.4-4.6m when $^{w}/_{b}$ = 0.3 (or in the range of 2.8-5.6m when $^w/_b$ = 0.4 to 0.5). in all other cases, probabilistic model could be used to transform the variables in order to be valid for the particular length.

ii. That the characteristic length of reinforcing steel and the acceptable threshold applied to life-size reinforced concrete structures exposed to cyclic wetting/drying weather condition can be obtained via this probabilistic assessment model.

The probabilistic assessment of acceptable threshold for smaller (or larger) lengths of specimen outside the range requires that acceptable chloride threshold be adjusted by shifting the chloride threshold value accordingly.

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