MODEL FOR A QUANTITATIVE CORROSION DAMAGE FUNCTION FOR REINFORCED CONCRETE MARINE SUBSTRUCTURE
(SUMMARY PAPER)

A. A. Sagüés, S.C. Kranc
Department of Civil and Environmental Engineering
University of South Florida
Tampa, Florida 33620, U.S.A.

ABSTRACT

A method of generating a quantitative corrosion damage function given the concrete properties, the configuration of the substructure and basic assumptions about corrosion mechanisms is presented. The output of the model is the amount of damage requiring repair at different elevations in the substructure as a function of time. The model is illustrated for a partially submerged marine substructure column. The damage function is developed from three sequential computational model modules concerning chloride ion transport, corrosion distribution, and evaluation of surface damage. The quantitative model output is illustrated for the different stages of deterioration of the system and for corrosion protection alternatives.

Keywords: Corrosion, Concrete, Reinforcement, Computation, Modeling, Damage Function.

RESUMEN

Se demuestra un método para generar cuantitativamente una función de deterioro debido a la corrosión dadas las propiedades del concreto, la configuración de un elemento de subestructura y las suposiciones básicas sobre los mecanismos de corrosión. El resultado del modelado es la cantidad de deterioro que requiere reparaciones a varias altitudes en la subestructura en función del tiempo. El modelo es ejemplificado para una columna de subestructura en ambiente marítimo. La función de deterioro se desarrolla a partir de tres módulos computacionales sucesivos para el transporte de cloruros, la distribución de corrosión, y la evaluación del deterioro visible. El modelo cuantitativo es ilustrado para diferentes etapas de deterioro del sistema y para varias alternativas de protección de la corrosión.

Palabras clave: Corrosión, Concreto, Refuerzo, Computación, Modelado, Función de Deterioro.

INTRODUCTION AND APPROACH

The corrosion limited service life of reinforced concrete structures has been conceptualized as a two-step deterioration model (Tuutti[1]). In that model the service life is divided into a corrosion initiation stage (chloride intrusion in progress but steel not yet activated) and a corrosion propagation stage (starting when chloride concentration at steel surface reaches the threshold value C_T) during which actual corrosion damage occurs. The useful service life of the

structural element is reached when corrosion damage exceeds an acceptable limit. The objective of this paper is to outline a method of generating a quantitative corrosion damage function that considers both the initiation and propagation stages, for a system that includes multiple individual elements.

The method is illustrated for a marine reinforced concrete structure, in which surface chloride content, concrete resistivity and oxygen diffusivity vary as a function of elevation with respect to the waterline. In addition, the model considers the expected variation of C_T with steel potential [2].

The entire system is initially considered to be in the passive state, and the open circuit potential is not a strong function of elevation. Chloride ions begin to penetrate to different extent at various elevations, depending on the surface chloride content. The evolution of chloride concentration as a function of potential and time is calculated by means of a *chloride transport module* that assumes diffusional chloride transport. Eventually, C_T is first reached at an elevation with fast chloride accumulation and steel depassivates locally. That causes a local potential change, and formation of a corrosion macrocell which depresses potential at the active spot and in the passive steel nearby. The redistribution of potentials and resulting corrosion rates are calculated using a *corrosion distribution module* based on previously developed computation methodology [3]. Since C_T is potential dependent, steel depassivation is not likely to happen next at spots immediately adjacent to the region of potential depression, but rather at other places with the appropriate combination of sufficiently high potential and chloride contamination. Every time an additional spot becomes active the potential distribution becomes readjusted and so does the C_T distribution. As each spot enters the active corrosion condition, the corrosion distribution module calculates the local corrosion rate, which is integrated as a function of time and converted into local corrosion penetration by means of the *surface damage evaluation module*. This module also compares the local penetration with a value M_{crit} assumed to result in concrete cover spalling for the combination of steel bar (rebar) diameter and concrete cover used at that location of the system [4,5]. When M_{crit} is reached at a given element of the system, the element is declared damaged and its projected area on the external concrete surface counted as damaged area. The sum of damaged area for the entire system as a function of time is defined as the *damage function* of the system.

EXAMPLE AND DISCUSSION

Figure 1 shows the system chosen for illustration, a partially submerged marine substructure column which is similar to the one described in Ref. 3 with the addition of an assumed surface chloride concentration (C_S) profile. The column is radially symmetric and it is divided into 101 vertical nodes and 36 radial nodes. The dimensions and assumed parameter values (which are generally representative of typical values encountered in field applications) are shown in Table 1. C_T is assumed to follow a dependence with potential given by $C_T = C_{T0} 10^{**}(E_i - E_{T0})/\alpha$, which is on the order of the dependence of pitting potential with chloride concentration threshold used in cathodic prevention investigations [2]. The values of the parameters for C_T are given in Table 1. M_{crit} was taken to be 0.01 cm, in the range of reported values [4,5]. Chloride diffusivity was for simplicity assumed to be elevation-independent. The corrosion distribution was computed as shown in Reference 3, with the addition of an assumed value i_p for the passive steel corrosion current density. Figure 2 shows the computed local potentials (for ring-shaped sections of reinforcement treated as a pervious metal sheet as detailed in Ref. 2) as function of elevation for different ages of the column. At time 0 years the potential is nearly uniform and in the passive range for all elevations. At time 21.4 years the first depassivation takes place, just above the water line where the surface chloride concentration was highest. The potential in adjacent nodes is also affected. By time 32.3 years several other ring regions have become depassivated, but the cathodically "prevented" intermediate regions remain passive. At time 33 years the submerged region becomes active. By time 63.4 years a mature corrosion pattern has developed. Figure 3 shows the correponding corrosion rates. It should be noted that the submerged portion, although active since year 32.3, always corrodes very slowly because the assumed value for oxygen diffusivity below water (water saturated concrete) is much smaller than for the regions above water [1,6]. Figure 3 (top) shows the computed corrosion charge per unit area (integration of corrosion rate with time) for each steel element that becomes active. While nearly straight, each plot is actually a curve reflecting the integration of varying corrosion rates with time. The horizontal dashed line is the Faradaic equivalent of $M_{crit}=0.01$ cm. Thus for example, the first element to become active (at 21.4 years) reaches M_{crit} at about 25 years and is declared spalled at that moment. The next two elements to spall do so at approximately year 30.5 and year 31 respectively. The damage function for the system, expressed as the total count of

spalled elements (each corresponding to about 0.39 m^2 of external column surface) is shown in the bottom graph of Figure 3.

Given the unit cost per m^2 of a given repair method, the damage function in the form shown in Figure 3 is directly convertible into accumulated repair cost needs. The predicted damage function can therefore be a powerful means of assessing cost effectiveness of design and rehabilitation alternatives. The ability to simulate various corrosion protection alternatives is shown in Figure 4. These are examples of predicted damage functions for a case with poorer concrete properties (Case B, same as in Table 1 but with $\rho_{H/L} = 2 \cdot 10^3 / 10^4$ ohm-cm; $D_{H/L} = 10^{-4} / 10^{-3}$ cm^2/sec; $D_{Cl} = 2 \cdot 10^{-7}$ cm^2/sec), and case B but with a submerged bulk anode (operating voltage assumed to be -1 V CSE) applied from year 0, or a surface anode of the sprayed zinc type [7] (operating voltage -0.5 V CSE at the concrete surface, also applied since year 0), or the use of an admixed corrosion inhibitor that elevates the value of C_{T0} by a factor of 10 with respect to the value in Table 1. The relative gain effected by each alternative can be easily evaluated by comparing the damage functions; absolute cost comparisons can be made by multiplying by the corresponding cost factors of each option.

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TABLE 1

Model Parameters

Steel Cover	$c =$	10.5 cm		
Column diameter	$w=$	105 cm		
Column Length	$L=$	1200 cm		
Concrete Resistivity	$\rho_H=$	10^5 ohm-cm		
	$\rho_L=$	$2 \cdot 10^4$ ohm-cm		
Oxygen Diffusivity	$D_H=$	10^{-3} cm^2/sec		
	$D_L=$	10^{-5} cm^2/sec		
Chloride Diffusivity	$D_{Cl}=$	$2 \cdot 10^{-8}$ cm^2/sec		
O$_2$ Surface Concentration	$C_{O2}=$	$2.5 \cdot 10^{-7}$ mol/cm^3 (in pore water)		
Cl$^-$ Surface Concentration	$C_{SH}=$	15 Kg/m^3		
	$C_{SW}=$	0 Kg/m^3		
	$C_{SL}=$	9 Kg/m^3		
Chloride Threshold Parameters	$C_{T0}=$	0.71 Kg/m^3		
	$E_{T0}=$	-128 mV		
	$\alpha =$	400 mV		
Polarization Parameters	E_0 (-mV CSE)	i_0(A/cm^2)	Tafel Slope (mV)	
Iron Dissolution	780	$1.875 \cdot 10^{-8}$	60	
Oxygen Reduction	-160	$6.25 \cdot 10^{-10}$	160	
Steel Passive Current Density	$i_p = 0.058 \cdot 10^{-6}$ A/cm^2			

Note: See Ref. 3 for further definitions and conventions used.

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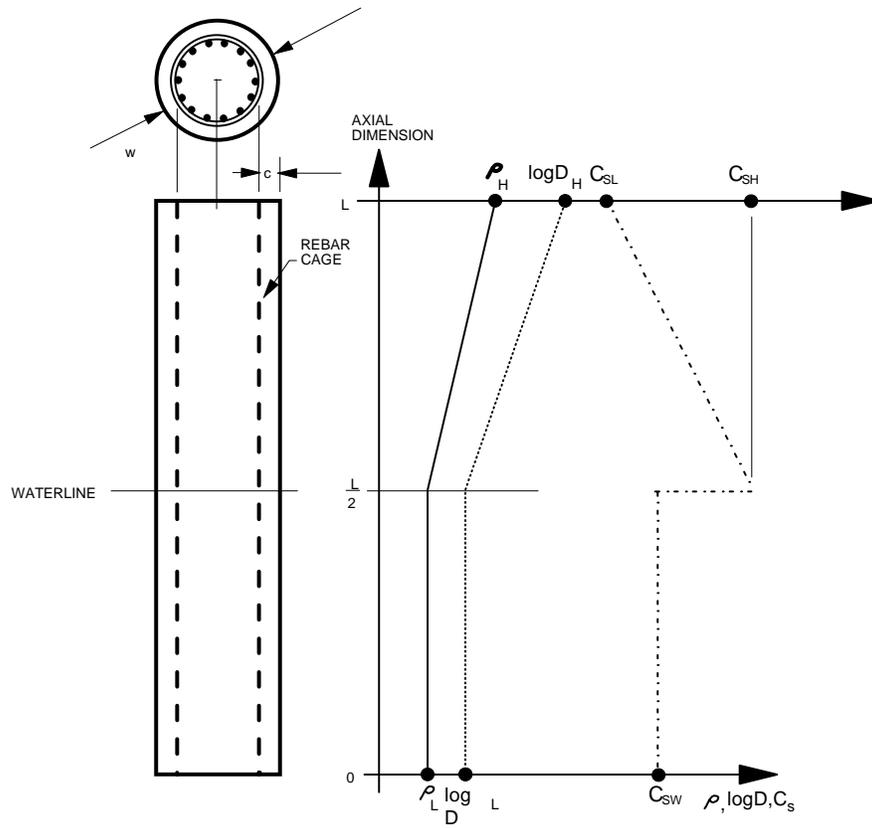7.   Sagüés, A. and Powers, R., **Corrosion**, Vol. 52. p.508, 1996.

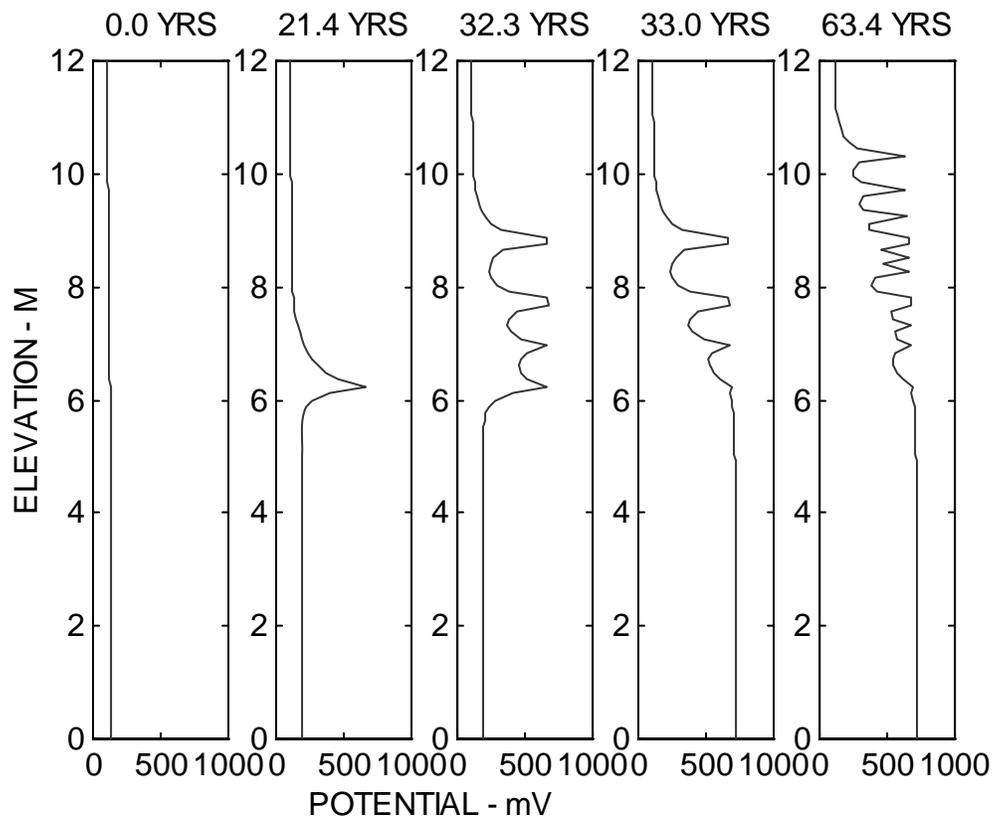Figure 1: Configuration of the system modeled.

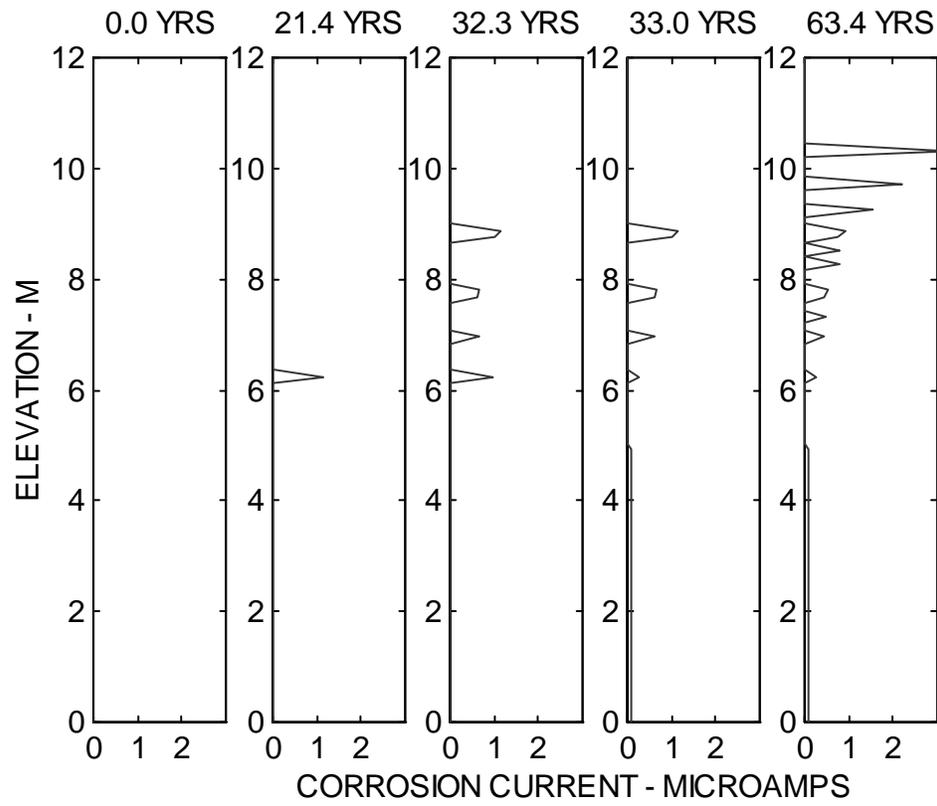Figure 2: Corrosion potential as a function of elevation at various times.

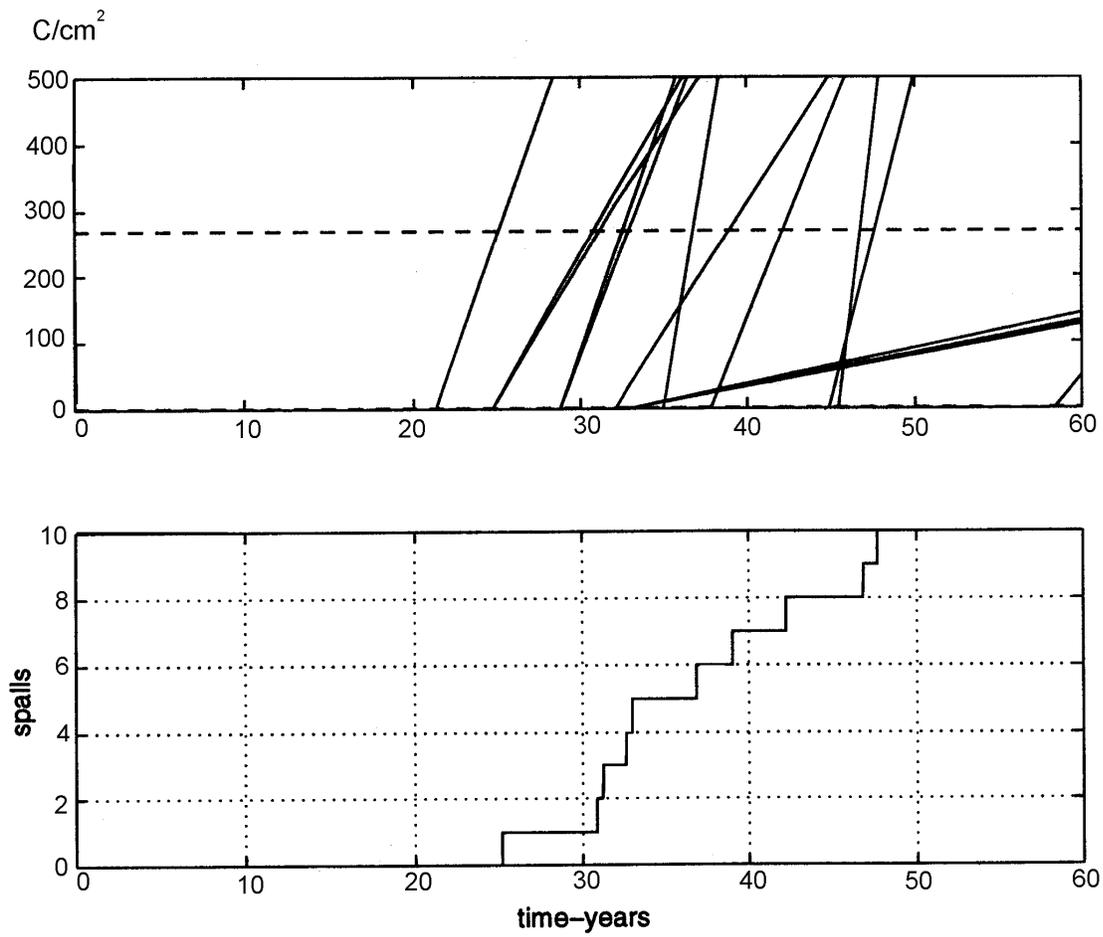Figure 3: Corrosion current as a function of elevation at various times. Element area = 0.39 m^2.

Figure 4: Top: Cumulative corrosion charge of the various activated elements as function of time. Bottom: Damage function. Each element has area = 0.39 m^2.
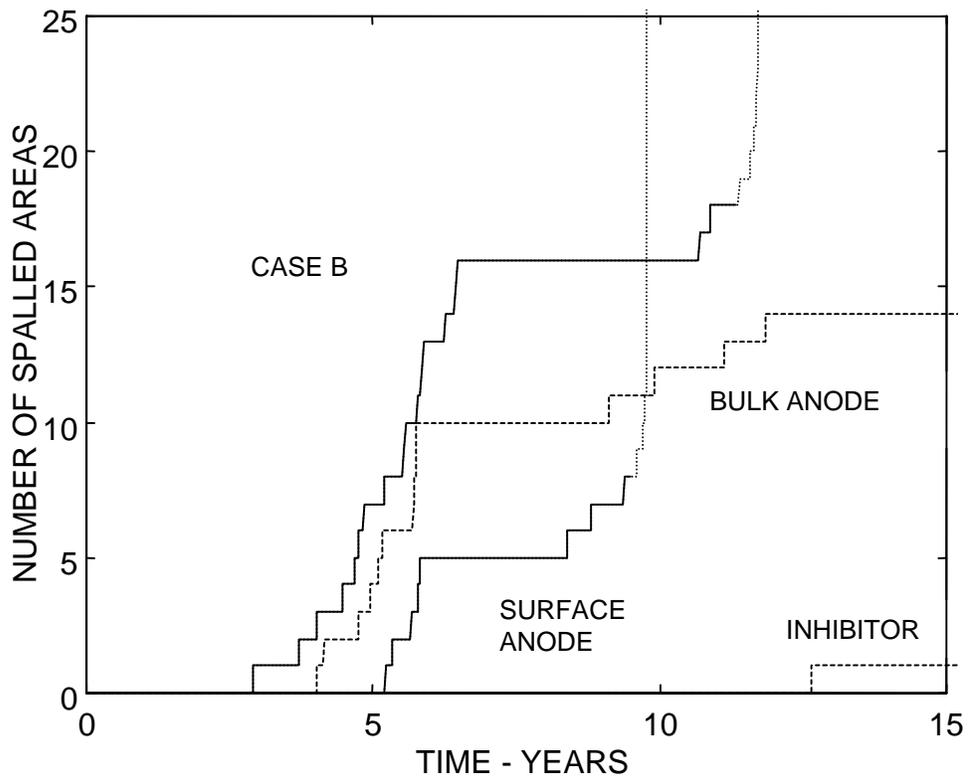
Figure 5: Example of damage functions for case B and corrosion mitigation alternatives.