A NEW SERVICE LIFE PREDICTION OF REINFORCED CONCRETE STRUCTURES DUE TO CHLORIDE-INDUCED COVER CRACKING WITH THE CONFINEMENT EFFECT

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This thesis is dedicated to my children, Khairul Elman Syah bin Khairulnizam who has accompanied me at the very beginning of this PhD journey, since he was 6 months old baby, which at that time he cannot say any word and now he is eleven years old…keep standing next to me, supporting me by saying, “mama…please don’t give up!”

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and the last one who has born at the very end of this journey is Khairul Emran Syah bin Khairulnizam who has shown me the miracle of life can happen with Allah’s wills.

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ABSTRACT

Corrosion in reinforcing steel is an important mechanism that reduces the service life of reinforced concrete (RC) structures exposed to the marine environment. It is essential to produce an advanced method that assists in making reliable predictions for the service life of RC structures to assist cost-effectiveness in life span of asset management. This thesis aims to develop a probabilistic-based model to predict the probability of damage in RC structures due to chloride-induced concrete cover cracking. The probabilistic model developed in this thesis considers modifying the existing crack propagation model previously developed by Mullard and Stewart (2011). This research improved the existing crack propagation model by conducting two series of accelerated corrosion tests based on bidirectional (two-way) RC slab specimens. The modified crack propagation model is proposed by considering the effects of reinforcement confinement and spacing of reinforcing bars. The key variables in the crack propagation model are spatial random variables. Partly due to the variability in the quality of workmanship, environmental and material. One of the required statistical parameter for spatial variables include the scale of fluctuation. Since the data for the scale of fluctuation is scarce, the second major finding from this study is to propose a new value of the scale of fluctuation for concrete compressive strength using the Curve fitting method and the Kriging method. Finally, the modified crack propagation model for predicting the crack propagation time was then developed, then the most reliable value for the scale of fluctuation of concrete compressive strength was determined. The modified crack propagation model and the new scale of fluctuation of concrete compressive strength are used to predict the service life of RC structures due to chloride-induced cracking. By modelling spatial variability and incorporation with the Monte Carlo simulation method, the probability of corrosion damage can be measured at any time during the service life of RC structures.

ABSTRAK

Proses pengaratan yang berlaku terhadap besi tetulang di dalam struktur konkrit bertetulang (RC) adalah mekanisme penting yang dapat mengurangkan hayat perkhidmatan struktur konkrit bertetulang apabila terdedah kepada persekitaran laut. Adalah penting untuk menghasilkan kaedah yang terkini untuk membantu membuat ramalan yang boleh dipercayai untuk mengetahui jangka hayat perkhidmatan sesebuah struktur RC untuk mencapai keberkesanan kos dalam pengurusan aset sepanjang hayat. Kajian ini dijalankan untuk memperbaiki model penyebaran retak yang sedia ada dengan menjalankan ujian kakisan yang dipercepatkan berdasarkan spesimen 'slab RC' dua hala. Pemboleh ubah dalam model penyebaran retak ialah pemboleh ubah rawak 'spatial'. Ini disebabkan oleh variasi kualiti mutu kerja, alam sekitar dan material. Salah satu maklumat statistik yang diperlukan untuk pembolehubah 'spatial' ialah skala turun naik. Oleh kerana data untuk menentukan skala turun naik adalah terhad, kajian ini mencadangkan nilai baru skala turun naik untuk kekuatan mampatan konkrit dengan menggunakan kaedah 'Curve Fitting' dan kaedah 'Kriging'. Model penyebaran retak yang diubah suai untuk meramalkan masa penyebaran retak berdasarkan ujian kakisan kemudian dibangunkan dan nilai yang sesuai untuk skala turun naik kekuatan mampatan konkrit dapat ditentukan. Persamaan diubahsuai untuk model penyebaran retak dan skala baru turun naik kekuatan mampatan konkrit digunakan untuk meramalkan hayat perkhidmatan struktur RC. Kajian ini tertakluk kepada retak yang disebabkan oleh serangan ion klorida. Dengan memodelkan kebolehubahan 'spatial' serta menggabungkan kaedah simulasi 'Monte Carlo', kemungkinan dan sejauh mana kerosakan kakisan boleh diukur pada bila-bila masa di sepanjang hayat perkhidmatan sesebuah struktur konkrit bertetulang.

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LIST OF SYMBOLS AND ABBREVIATIONS

a_m	-	percentage of magnetite (%)
a/c	-	aggregate cement ratio
A	-	total area of structure (m^2)
b_g	-	percentage of geothite (%)
c_e	-	percentage of lepidocrocite (%)
C	-	insitu concrete cover (mm)
C(x,t)	-	chloride content at a distance x from the concrete surface at time t
C_{cr}	-	chloride threshold concentration (kg/m^3 concrete)
$C_{i,j}$	-	the i, j th element of the covariance matrix
C_{mean}	-	mean concrete cover (mm)
C_{nom}	-	nominal design concrete cover (mm)
C_{fc}	-	concentration of free chloride ions (kg/m^3)
C_0	-	surface chloride concentration (kg/m^3 concrete)
d_a	-	density of magnetite
d_b	-	density of goethite
d_c	-	density of lepidocorcite
d	-	correlation length
d_{dis}	-	distance from the coastline (km)
d_s	-	thickness of corrosion products to cause cracking (mm)
d_x	-	a measure of the correlated length (i.e. a function of the scale of fluctuation) between elements in the x-direction of a random field (m)
d_y	-	a measure of the correlated length (i.e. a function of the scale of fluctuation) between elements in the y-direction of a random field (m)
d_z	-	a measure of the correlated length (i.e. a function of the scale of fluctuation) between elements in the z-direction of a random field (m)

d_0	-	thickness of porous zone around reinforcing bar (μm)
D	-	reinforcing bar diameter (mm)
D_c	-	chloride diffusion coefficient (m^2/s)
$D_{c,ref}$	-	chloride diffusion coefficient at reference conditions (m^2/s)
D^*_c	-	apparent chloride diffusion coefficient (m^2/s)
D^*_h	-	apparent humidity diffusion coefficient (m^2/s)
$D_{Cl,H2O}$	-	diffusion coefficient of chloride in an infinite solution (m^2/s)
erf		Erf error function
$E_c(t)$	-	concrete elastic modulus (MPa)
$E_{ef}(t)$	-	effective concrete elastic modulus (MPa)
f_c	-	insitu concrete compressive strength(MPa)
f_{cyl}	-	concrete standard test cylinder compressive strength (MPa)
f_{spec}	-	concrete cylinder compressive strength, corrected for workmanship (MPa)
f_t	-	concrete tensile strength (MPa)
F'_c	-	design concrete compressive strength (MPa)
g/c	-	gravel cement ratio
h_{nom}	-	depth of a concrete column in the direction of concrete cover (mm)
i_{corr}	-	corrosion rate ($\mu A/cm^2$)
$i_{corr(repair)}$	-	corrosion rate of repair material ($\mu A/cm^2$)
$i_{corr(exp)}$	-	corrosion rate during accelerated corrosion testing ($\mu A/cm^2$)
$i_{corr(real)}$	-	corrosion rate of real RC structures used for correcting times to cracking based on accelerated corrosion testing ($\mu A/cm^2$)
k_c	-	curing factor
k_{ccf}	-	confinement correction factor
k_{cp}	-	compaction coefficient
k_p	-	rate of rust production
k_w	-	workmanship factor
JKR	-	Jabatan Kerja Raya
L	-	lower triangular matrix formulated from the decomposition of the covariance matrix

m	-	number of maintenance actions
M_{crit}	-	amount of rust products to cause crack initiation
R_{icorr}	-	ratio of higher to lower corrosion rate used for calculating the rate of loading correction factor
s/c	-	sand/cement ratio
$t_{cr(exp)}$	-	time to reach a limit crack width observed during accelerated testing (years)
$t_{cr(real)}$	-	time to reach a limit crack width for real structures calculated using rate loading correction factor (years)
t_{ser}	-	time from crack initiation to limit crack width for time-invariant corrosion rate (years)
t_{1st}	-	time to first cracking; time from corrosion initiation to crack initiation for time invariant corrosion rate (years)
t_i	-	time to corrosion initiation (years)
t_{sp}	-	time to excessive cracking; time from corrosion initiation to limit crack width for time invariant corrosion rate (years)
U_c	-	activation energy of the chloride diffusion process
W	-	vector of spatially correlated random variables
w_c	-	absorption isotherm
$w_{cr}(t)$	-	crack width at time t (mm)
w_{lim}	-	limit crack width (mm)
w_{1st}	-	crack width at time of first cracking (mm)
w/c	-	water cement ratio
x_{1st}	-	reduction in reinforcing bar diameter to cause crack initiation (mm)
Z	-	a vector of uncorrelated standard random variables
α	-	empirical constant for time variant corrosion rate
α_a	-	volumetric expansion ratio of magnetite
α_b	-	volumetric expansion ratio of goethite
α_c	-	volumetric expansion ratio of lepidocorcite
α_r	-	volumetric expansion ratio of rust
β	-	empirical constant for time-variant corrosion rate

γ_{icorr}	-	repair efficiency factor for corrosion rate (%)
Δ	-	discretised element size (m)
$\Delta P_{f,i}$	-	probability that extent of damage exceeds the repair threshold between inspections
Δt	-	inspection interval (years)
Δ_{Ti}	-	repair efficiency factor for corrosion initiation (years)
θ	-	scale of fluctuation of random field (m)
μ_N	-	non stationary mean of a random field for concrete compressive strength in a RC column (MPa)
μ	-	stationary mean of a random field for concrete compressive strength in a RC column (MPa)
$\rho_{(\tau)}$	-	correlation function for a random field
ρ_a	-	density of aggregate (kg/m^3)
ρ_c	-	density of cement (kg/m^3)
ρ_r	-	density of rust (kg/m^3)
σ	-	standard deviation
τ_x	-	distance, in the x-direction, between the centroid of correlated elements in a random field
τ_y	-	distance, in the y-direction, between the centroid of correlated elements in a random field
τ_z	-	distance, in the z-direction, between the centroid of correlated elements in a random field
ν_c	-	Poisson's ratio of concrete
φ_{cr}	-	concrete creep coefficient
ψ_{cp}	-	cover cracking parameter

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