SPATIAL TIME-DEPENDENT RELIABILITY ANALYSIS OF CARBONATION INDUCED CORROSION DAMAGE TO RC STRUCTURES UNDER A CHANGING CLIMATE AND COST-BENEFIT ANALYSIS OF CLIMATE ADAPTATION STRATEGIES

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Thesis submitted for the degree of Doctor of Philosophy

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January 2015

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

Lizhengli Peng

Acknowledgement

First and foremost I would like to express my sincere gratitude to my supervisor Professor Mark Stewart. I am extremely lucky to be his PhD student. His vast knowledge and skill, as well as his enthusiasm for research, has guided and motivated me to proceed through the doctoral program and complete my thesis. My sincere thanks goes to Professor Stewart for his contributions of time, ideas and inputs to make my PhD experience rewarding. I also appreciate his encouragement and the various opportunities he provided me to explore not only the beauty of research but also the outside world.

I would like to gratefully acknowledge the financial support provided by the University of Newcastle International Postgraduate Research Scholarship (UNIPRS) and University of Newcastle Postgraduate Research Scholarship (UNRSE) scheme for my PhD scholarship and also to Professor Mark Stewart for his financial support.

I acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and I thank the climate modelling groups for producing and making available their model output. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provide coordinating support and led the development of software infrastructure in partnership with the Global Organisation for Earth System Science Portals. I also would like to express my appreciation to Dr Xiaoming Wang and Dr Stacey Dravitzki of CSIRO for providing climate data for Australian and Chinese cities. Many thanks go to Dr Lijun Zhu and Dr Xianfeng Liu from the University of Newcastle for their inspiring discussions.

I also would like to thank all my friends in Newcastle, who accompanied and helped me while studying overseas alone. Their kindness and friendship made my life in Australia much easier and happier.

I wish to thank my parents. Their unflagging support, encouragement and love have allowed me to pursue my dreams and were my driving force. For that, I cannot thank them enough.

Finally, I would like to acknowledge my husband Zhang Liu, for his continuous support, encouragement, love and friendship throughout all these years.

List of Publications

Conference papers:

Peng, L., & Stewart, M.G. (2014). Climate Change and Corrosion Damage Risks for Concrete Structures in China. 6th International Conference on protection of structures against hazards, Tianjin, China, 16-17 October.

Peng, L., & Stewart, M.G. (2013). Corrosion and Damage Risks for Reinforced Concrete Infrastructure in China Due to a Changing Climate. 11th International Conference on Structural Safety & Reliability, New York, NY, U.S.A, June 16-20.

Peng, L., & Stewart, M.G. (2012). Deterioration of concrete structures in Australia under a changing climate. Proceeding of the 22nd Australasian conference on the mechanics of structures and materials, Sydney, Australia, 11-14 December.

Stewart, M.G., Peng, L., & Wang, X. (2012). Impact of Climate change on corrosion and damage risks to concrete infrastructure. 37th Conference on Our World in Concrete & Structures, Singapore, 29-31 August.

Journal papers:

Peng, L., & Stewart, M.G. (2015). Damage risks and cost-benefit analysis of climate adaptation strategies of RC structures in Australia. Concrete in Australia.

Peng, L., & Stewart, M.G. (2014). Climate change and corrosion damage risks for reinforced concrete infrastructure in China. International Journal of Structure and Infrastructure Engineering.

Peng, L., & Stewart, M.G (2014). Spatial Time-Dependent Reliability Analysis of Corrosion Damage to Concrete Structures under a Changing Climate. Magazine of Concrete Research.

Peng, L., & Stewart, M.G. (2014). Changing Climate Effects on Carbonation-induced Corrosion and Damage Risks of RC Infrastructure in China. China Civil Engineering Journal.

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Nomenclature

A = penetrated area (m^2);

a = binding capacity for CO_2 (kg CO_2/m^3);

a' = inner radius;

B(n-1, N, θ(t)) = the cumulative Binomial distribution;

B(t) = benefits at time t ;

b = a model parameter defined as b = θ/2 where θ is the scale of fluctuation;

b' = outer radius;

C_s = CO_2 concentration at the surface (kg CO_2/m^3);

C_{CO_2} = atmospheric CO_2 concentration (g cm^{-3});

C = the concrete cover (mm);

C_D = the design cost;

C_C = the construction cost (materials and labour);

C_{QA} = the cost of quality assurance/control;

C_{IN} = the cost of inspections;

C_{PM} = the cost of preventative maintenance;

C_{CM} = the cost of corrective maintenance;

C_{USE} = the user delay cost;

C_F = the cost of durability failure;

C_{adapt} = defined as the extra costs to take adaptation measures for unit area ($/$m^2$);

C_{damage} = the cost of damage including maintenance and repair costs, user delay and disruption costs, and other direct or indirect losses arising from damage to infrastructure ($/$m^2$);

$C_{CO_2}(t)$ = the time-dependent increase in atmospheric CO_2 concentration (10^{-3} kg/m^3);

C_e = cement content (kg/m^3);

C_aO = C_aO content in cement;

$C_{i,j}$ = the value of the covariance matrix;

COV_{ME} = the coefficient of variation of model error;

$COV_{T/C}$ = the coefficient of variation obtained directly from the comparison of the actual and predicted values;

COV_{test} = the coefficient of variation of measurement of the data;

COV_{spec} = the coefficient of variation of the specimen properties;

C_{mean} = the mean concrete cover (mm);

C_{nom} = the nominal or design cover (mm);

C_{repair} = direct costs of repair of corrosion damage ($/m^2);

C_{cv} = construction cost per unit volume;

C(t) = costs at time t;

c_1 = external concentration of carbon dioxide (g/m^3);

c_2 = the concentration of carbon dioxide at the carbonation front in g/m^3;

c = a model parameter defined as c= θ/4;

D_{CO2} = the diffusion coefficient for carbon dioxide through carbonated concrete in m^2/s;

D_{eff} = effective diffusion coefficient at defined compaction, curing and environmental conditions (m^2/s);

D_1 = CO_2 diffusion coefficient after one year;

$D_{CO2}(t)$ = the time-dependent CO_2 diffusion coefficient;

D_{bar} = diameter of the steel reinforcing bar (mm);

D = slab depth or beam width;

DH = degree of hydration;

d_x and d_y = the correlation lengths in the x and y axes, respectively;

d = the correlation lengths defined as $d = \theta/\sqrt{\pi}$;

$d_{crack}(t)$ = the extent of the concrete surface severe corrosion damage at time t;

E = the activation energy of the diffusion process (40 kJ/mol);

E_{ef} = the effective elastic modulus of concrete in (MPa);

E_c = the elastic modulus of concrete;

E[C] = expected service life costs for a RC bridge

$E_{SF}(T)$ = the expected cost of repair or rehabilitation of corrosion-induced damage during service life T;

$E[C_M]$ = the expected cost of maintenance;

$E[C_U]$ = the expected user cost due to maintenance disruptions;

$E[C_F]$ = the expected cost of failure during the service life of the bridge;

$\mathbf{E}_{W(X)\mathbf{v}}$ = the N × 1 vector containing the covariance of W(**X**) with the elements of **w**;

$E_c(t)$ = the time-dependent in-situ elastic modulus;

E_{ef} = the effective elastic modulus of concrete;

$E_{damage}(T)$ = the expected cost of repair or rehabilitation (maintenance) of corrosion-induced damage during service life T;

$E_{damage\text{-}BAU}(t)$ = the expected damage costs for business as usual(existing practice);

$E_{damage\text{-}adaptation}(t)$ = the expected damage costs for adaptation measures;

$F_R(x)$ = the cumulative distribution function of R structural resistances;

FV = the future cost;

F'_c = the nominal design concrete compressive strength;

F_1 = a random variable linking cube/cylinder strength to nominal compressive strength;

F_2 = a random variable relating 28-day in-situ strength to cube/cylinder strength;

f_t = concrete tensile (splitting) strength (MPa);

f_R = the probability density functions of R structural resistances;

f_S = the probability density functions of S structural load effect;

$f_T(t)$ = time-dependent change in diffusion coefficient due to changes in temperature;

$f_{RH}(t)$ = time-dependent change in diffusion coefficient due to changes in RH;

$f_t(t)$ = time-dependent in-situ concrete splitting tensile strength;

$f_c(t)$ = time-dependent in-situ concrete compressive strength;

f = the fluctuation scale;

$f_c(28)$ = the 28-day in-situ compressive strength;

f'_t = the design concrete tensile strength (MPa);

$f_{d_{crack}}\left(d_{crack}, t\right)$ = the multi-dimensional probability distribution of $d_{crack}(t)$;

GDP = Gross Domestic Product ($ trillion);

G = the limit state function;

$g_j(X, t)$ = the limit state function of element j;

g_e = a constant equal to 2.5;

h = equals to $\theta\sqrt{2}$;

$i_{corr-20}$ = the corrosion rate at 20 ℃ in l $\mu A/cm^2$;

i_{corr} = the corrosion current density in l $\mu A/cm^2$;

$i_{corr(real)}$ = the corrosion rate of the structure in the field (=100 $\mu A/cm^2$);

$i_{corr(exp)}$ = 100 $\mu A/cm^2$ is the accelerated corrosion rate ;

i = the number of inspection;

$i_{corr(ref)}$ = corrosion current density at reference state ($\mu A / cm^2$) and is time-invariant;

$i_{corr}(t)$ = time-dependent corrosion rate;

K_1 = constant parameter which considers the influence of execution on D_{eff} (e.g. influence of curing);

K_2 = constant parameter which considers the influence of the environment on D_{eff} (e.g. realistic moisture history at the concrete surface during use);

K = parameter of temperature impacts on corrosion rate;

$K_{N,n}$ = the number of combinations of elements that exceed critical percentage;

k_{urban} = the increased CO_2 levels in urban environments;

k_p = the rate of rust production;

k_R = a rate of loading correction factor;

k_c = the confinement factor that represents an increase in crack propagation around external (edge) reinforcing bars due to the lack of concrete confinement;

k = the total number of elements of the concrete surface;

k_{site} = factor to account for increased CO_2 levels in non-remote environments;

l = the length of beam;

L = the lower triangular matrix of the covariance matrix calculated by a Cholesky decomposition (or similar);

M = respective molar masses in (kg/mol);

M_{st} = the mass of corroded steel depends on the type of corrosion product;

$ME(r_{crack})$ = model error of crack propagation model;

M_{CaO} = molar mass of C_aO and equal to 56 g/mol;

M_{CO_2} = molar mass of CO_2 equal to 44 g/mol;

m = a mass of carbon dioxide (g);

m_i = the number of elements in the i^{th} combination;

N = the total number of elements;

n_y = the number of years in the future at which the cost is incurred;

n_c = constant parameter which considers the influence of meso climatic conditions (e.g. orientation and placing of structure);

n_d = the age factor of CO_2 diffusion coefficient;

n_m = an age factor of microclimatic conditions which related to the frequency of wetting-drying cycles;

n_e =the number of elements that exceed critical degradation;

n = the number of damage incidents;

P_f = the probability if durability failure;

$p_{s,n}(t)$ = the probability of the n^{th} damage incidence before time t;

RH = relative humidity (%);

R = the gas constant (8.314×10^{-3} kJ/mol· K);

r_{crack} = the rate of crack propagation (mm/hr);

r = the discount rate;

S = the space interval;

s = the location of the spatial random variable within the random field;

T_i = Corrosion initiation, the time from construction completed to the time when carbon dioxide or chlorides, etc. induced de-passivation of the protective alkaline film around the reinforcing bar (year);

t_{1st} = Crack initiation, the time from corrosion initiation to the time when the first visible crack of width of approximately 0.05 mm can be observed on the concrete surface (year);

T(t) = the temperature at time t (℃);

T_{sev} = the time to corrosion damage;

T = the service life of the structure (years);

t = time in service;

t_0 = reference period, e.g. 1 year;

t_{sev} = the time for a crack to propagate from crack initiation to a limit crack width;

$V_{f_c(28)}$, V_{F_1} and V_{F_2} = the COV of the 28-day in-situ concrete compressive strength, F_1 and F_2, respectively;

w = the crack width (mm);

w = a vector representing the value of the random field for each of N elements;

X(s) = the multidimensional random field;

X_i = the location of the centroid of the element i;

X = the averaging interval;

X_0 = the distance from the end of the first element to the start of the second element;

X_1 = the distance from the start of the first element to the start of the second element;

X_2 = the distance from the start of the first element to the end of the second element;

X_3 = the distance from the end of the first element to the end of the second element;

x = thickness of penetrated concrete layer (m);

$x_c(t)$ = the carbonation depth at time t;

Z = a vector of uncorrelated standard random variables;

α_H = a degree of hydration;

ΔA_s = the loss of steel cross section in (mm^2);

ΔA_{s0} = the loss of steel cross section that is needed for crack initiation in (mm^2);

ΔB = co-benefit of adaptation strategies;

Δt = the time between inspections;

$\Delta P_{s,i}$ = the probability of damage incident between the $(i-1)^{th}$ and i^{th} inspections;

$\Delta P_{f,i}$ = the probability that the extent of damage exceeds the repair threshold between the $(i-1)^{th}$ and i^{th} inspections;

$\Delta R(t)$ = the proportional reduction in damage losses due to an adaptation measure;

δ_s = the thickness of corrosion products to generate tensile stresses;

δ_0 = the thickness of the pore band around the reinforcing interface (μm);

ζ_i = the independent standard normal variates (zero mean, unit variance and zero correlations);

θ =the scale of fluctuation;

$\theta(t)$ = the probability of failure of the individual elements at time t;

θ_i = the eigenvalues of the covariance matrix;

θ_x and θ_y = the scales of fluctuation for a two-dimensional random field in x and y axes, respectively;

ρ_{rust} = the density of the corrosion products (kg/m^3);

$\rho(\tau)$ =the correlation coefficient between elements;

ρ_0 = the common correlation between all elements;

$\rho_{i,j}$ = the value of the correlation function between points i and j;

σ = the standard deviation of the random field;

τ = the distance between two elements in the random field;

τ_x and τ_y = the distances between the centroid of element i and j in the x and y axes, respectively;

υ = Poisson's ratio of concrete;

ψ_{cp} = the concrete cover cracking parameter;

φ_{cr} = the creep coefficient;

φ_i = the length of the element in a one-dimensional random field or the area of the element in a two dimension random field.

Abstract

The long term performance of infrastructure is an important consideration for asset owners, particularly in relation to reinforced concrete (RC) structures subject to corrosion. This thesis focuses on management of RC structures subject to carbonation induced corrosion under a changing climate. A changing climate may lead to increases in atmospheric CO_2 concentration, and changes in temperature and relative humidity (RH), especially in the longer term, will accelerate the deterioration processes and consequently decline the safety, serviceability and durability of RC infrastructure. Therefore, modelling the deterioration process of RC structures under a changing climate and estimating cost effectiveness of climate adaption strategies can provide very useful information in decision making for the management of RC structures in corrosive environments.

While there is much research on corrosion-induced deterioration of concrete structures, there is relatively little research on how deterioration can be affected by a changing climate. In this thesis, an improved carbonation induced corrosion model is developed by considering time-dependent atmospheric CO_2 concentration, local temperature and RH effects. A new parameter k_{site} is introduced to take account local differences in CO_2 concentration based on recorded data from various observation sites around the world. Future climates may be influenced by various factors which make projections difficult. Therefore, high and medium emission scenarios (i.e. RCP 8.5 and RCP 4.5), as well as a reference scenario, are used to cover the full range of possible outcomes.

Many corrosion parameters and concrete properties governing the corrosion process are uncertain. Moreover, due to the spatial variability of workmanship, and environmental and other factors, it is recognised that the material and dimensional properties of concrete structures will not be homogeneous. So, it is necessary to model the spatial variability of the parameters in order to be able to characterise not only the probability of degradation, but also the extent of damage. This information is useful in optimising maintenance strategies. Random field is used in this thesis to model the spatial variability of corrosion

damage. The method of discretisation and the random field parameters of element size, scale of fluctuation and correlation function are fully discussed in here.

In addition, a cost-benefit analysis of climate adaptation strategies is developed based on spatial time-dependent reliability analysis described above. Climate adaptation strategies such as increasing concrete cover and upgrading concrete strength, as well as a maintenance strategy are defined. The cost-effectiveness of an adaptation strategy is measured in terms of Net Present Value (NPV). Both the mean NPV and the probability of NPV exceeds zero can be calculated to provide useful information for decision makers.

RC beams and slabs for bridges and buildings in two Australian cities and three Chinese cities are investigated in the thesis. Durability design requirements, climate projections of specific locations and statistics of real structures' parameters (such as concrete cover and concrete compressive strength) of RC structures in Australia and China are considered in order to make practical predictions. Cost data for adaptation and corrosion damages are based on local market prices of the two countries. Monte-Carlo simulation is used as the computational method to do the spatial time-dependent reliability analysis which includes the time-dependent climate scenarios and deterioration processes, as well as a large number of random variables and spatial random fields of material properties and dimensions. Sensitivity analysis is performed in this thesis to estimate the relative influences of the considered random variables. Break-even analysis is also conducted to provide a straight forward measure for decision makers to quickly determine if an adaptation strategy is cost effective or not.

The overall results indicate that the reliability framework is well suited to predict carbonation induced corrosion damage of RC structures under a changing climate and assessing the cost-effectiveness of climate adaptation strategies. Moreover, the framework can easily adapt to updates or adjustments of information. The results and analysis can greatly assist designers and asset owner or operators in improving and optimising the management of RC structures in corrosive environments.