Virtual Corrosion Monitoring for Infrastructures Considering Environmental Uncertainty

Yuguo Yu (Presenter)

Wei Gao

Qihan Wang

Bin Dong

Centre for Infrastructure Engineering and Safety, School of Civil and environmental Engineering,
The University of New South Wales, Sydney, NSW 2052

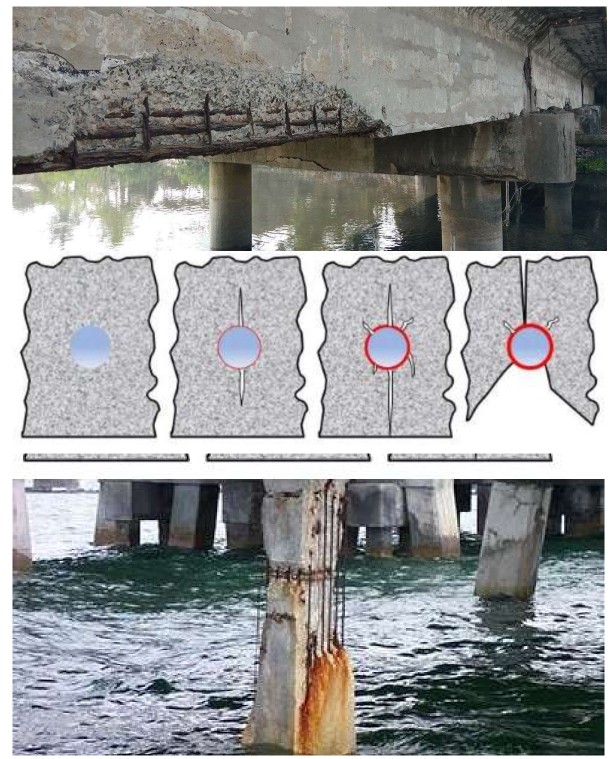
UNSW SYDNEY

Table of Contents:

- **What is “virtual corrosion monitoring”**

❖ Impact of corrosion on infrastructure

Reinforced concrete infrastructures have the potential to be very durable and capable of withstanding a variety of adverse loading as well as environmental conditions. However, failures in the structures do still happen as a result of premature steel reinforcement corrosion caused by various aging-related reasons, such as concrete leaching, carbonation, and chloride ingress.



Corrosion → Cracking → Failure

❖ Physical corrosion monitoring & its limitation

Physical monitoring by non-destructive testing methods:

✓ Corrosion potential and concrete resistivity measurement

✓ Steel polarization measurement

✓ Ultrasonic pulse velocity technique

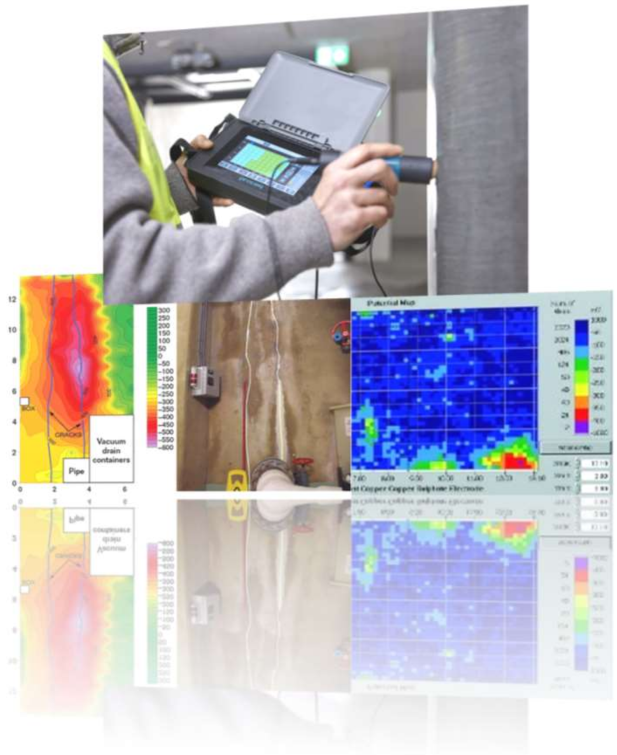
✓ Visual inspection through X-ray, Gamma radiography etc.

Limitations:

× Provide only instantaneous estimation

× Hard to determine representative corrosion state

× Incapable of provide aging corrosion diagnosis



❖ Concept of virtual corrosion monitoring

The use of scientifically robust modelling techniques to provide ***high-fidelity numerical representations*** to describe comprehensively the whole process from concrete multi-aging induced corrosion initiation to active corrosion propagation, and rust-induced cracking.

❖ Significance of virtual corrosion monitoring

Supplement greatly to the actual physical monitoring with extra functionalities of diagnostic prediction at multiscale levels through mimicking the reality with the established high-fidelity digital counterpart.

- **Core techniques**

❖ Essential numerical components

- ➢ Chemo-physical-mechanical (CPM) concrete *aging* model
- ➢ Electrochemical (EC) *corrosion* model
- ➢ Robust *solver* and *coupling* scheme

+

- ➢ Efficient *uncertainty* analysis method

Pre-processing

- Determine the initial durability-related properties for the entire corrosion cell, both concrete and embedded steel reinforcements
- Define time-dependent boundary $BC(t)$ representing service condition

Time-dependent CPM-EC numerical modelling

while $t \leq$ *the designated exposure duration*, do

1. Draw $BC(t)$ as the boundary condition for current time step
2. Model multi-species transportation (***CPM-I***)
3. Model chemical interaction of cement hydrates under the ingress of external aggressive agents (***CPM-II***)
4. Evaluate influences of concrete decay on the chemophysical and electrochemical properties of the system, i.e. the corrosion cell (***CPM-III***)
5. Perform steel corrosion modelling (***EC***)
6. Update the CPM and EC properties of corrosion cell
7. $t = t + \Delta t$; Δt

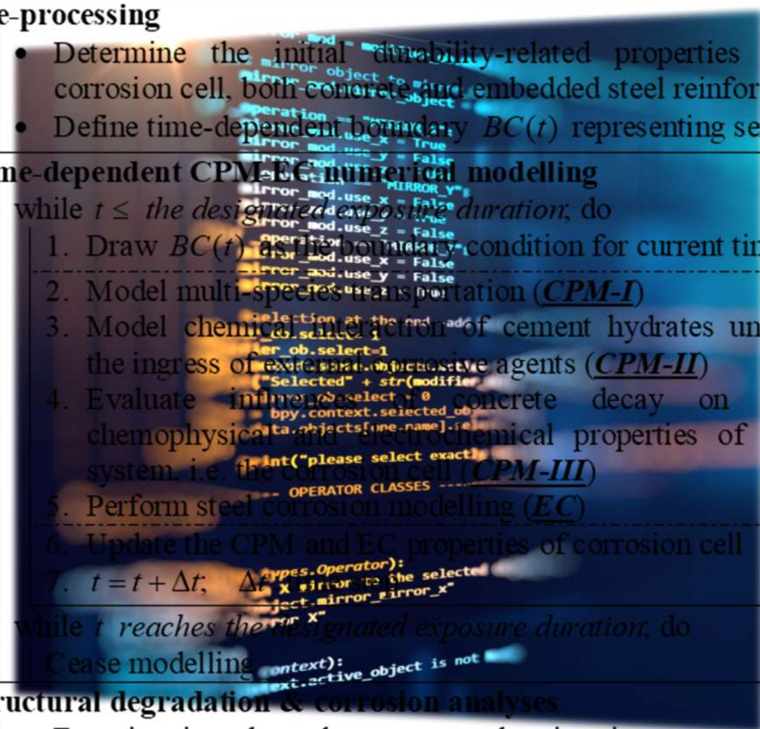
Operator Splitting Approach (OSA)

while t *reaches the designated exposure duration*, do

Cease modelling

Structural degradation & corrosion analyses

- Examine time-dependent concrete deterioration
- Examine time-dependent corrosion propagation



❖ Chemo-physical-mechanical (CPM) concrete aging model

➢ CPM-I for multi-species transportation

Addressing a multi-species transportation problem is in fact solving partial differential equations of multiple degrees of freedom. The *general mathematical expression* can be written as:

$$\frac{\partial \boldsymbol{c}}{\partial t} = \operatorname{div}\left[\boldsymbol{D}\operatorname{grad}(\boldsymbol{c})\right] + \tilde{f} \circ \boldsymbol{c}$$

where $\boldsymbol{c}(D,t) \in \Re$ is ionic concentration tensor defined on space domain *D* and time domain *t*, $\boldsymbol{D}$ is diffusivity tensor, and $\tilde{f}$ indicates the operator of all potential coupling terms.

Electrical neutrality; Chemical activity; heat conduction; Advection

❖ Chemo-physical-mechanical (CPM) concrete aging model

➢ CPM-II for chemical reaction

Evaluating reactions as triggered due to multi-species transportation under OSA is centralised at calculating the algebraic equations of chemical equilibrium based on chemical thermodynamics. The *general mathematical expression* can be written as:

$$K_s = \prod_{i=1}^{N_1} \boldsymbol{c}_i^{\nu_{si}} \boldsymbol{\gamma}_i^{\nu_{si}} \Bigg/ \prod_{j=1}^{N_2} \boldsymbol{c}_j^{\nu_{sj}} \boldsymbol{\gamma}_j^{\nu_{sj}} = \prod_{i=1}^{N_1} \{\boldsymbol{c}_i\}^{\nu_{si}} \Bigg/ \prod_{j=1}^{N_2} \{\boldsymbol{c}_j\}^{\nu_{sj}} \text{, for } s = 1,\ldots,\mathrm{S}$$

where K_s is equilibrium constant (-) of the sth reaction, $[C_i], \gamma_i, \nu_{si}$ and $[C_j], \gamma_j, \nu_{sj}$ are concentration, activity coefficient and valence number of the ith product and the jth reactant respectively.

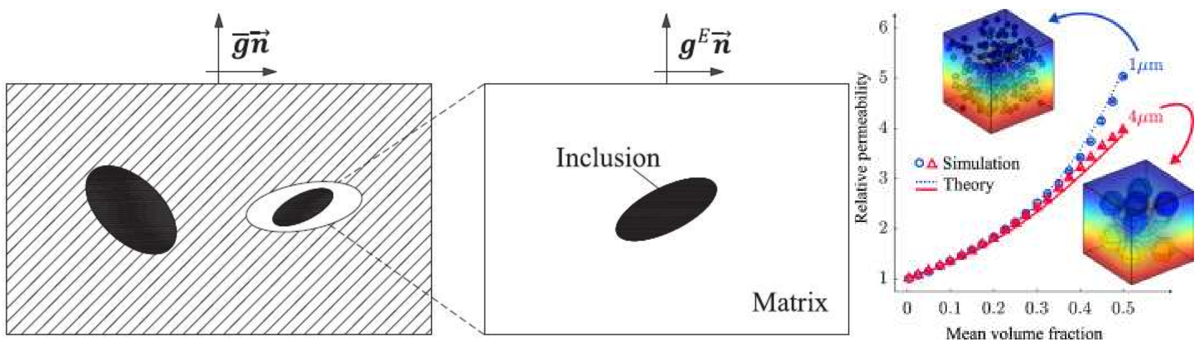
UNSW SYDNEY

❖ Chemo-physical-mechanical (CPM) concrete aging model

➢ CPM-III for damage evaluation

Elasticity; Chloride binding capacity; Resistivity

Assessing the damage to concrete due to the reactive transportation is mainly about evaluating the holistic CPM impact on the material as brought by micro-structural variations. To do so, an analytical micromechanical model, called mixed effective medium theory (MEMT), is incorporated to fulfill the comprehensive aging analysis.



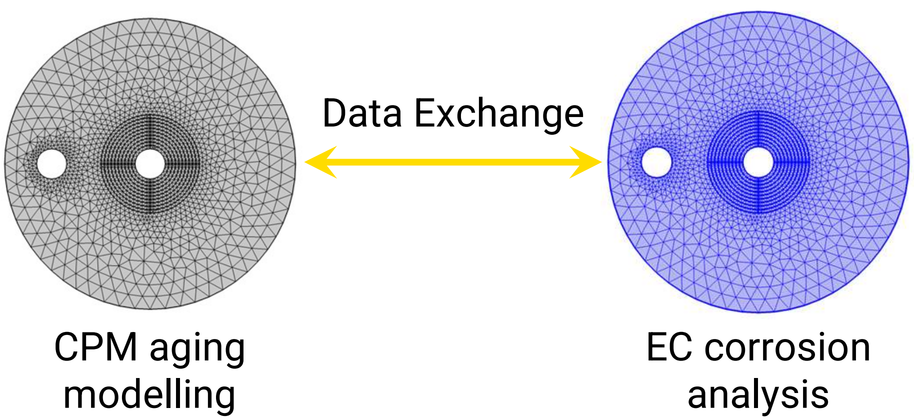
Representative element volume (REV) of MEMT

_Yu Y_, Zhang YX. Effect of capillary connectivity and crack density on the diffusivity of cementitious materials. Int J Mech Sci 2018; 144: 849-57.

❖ Electrochemical (EC) corrosion model

Based on the coupling scheme of OSA, corrosion study is carried out subsequentially following the CPM material aging analysis. Electrochemical (EC) model with incorporating Tafel equation to the boundary condition of steel polarisation is used. Finite element method is also adopted as solver to the EC model, as it facilitates not only the analysis on corrosion cells of arbitrary configurations, but also allows effective data exchange with CPM model.

Geometrical diversity; Material non-uniformity; Defect



❖ Efficient uncertainty analysis

In the quest of realising virtual corrosion monitoring, the high-fidelity numerical representation of the problem as well as the intended diagnostic ability are granted by the coupled CPM-EC model. However, to cast CPM-EC model in the context of ***uncertainty analysis***, which is an essential requirement for many field applications, may lead to major computational difficulty.

↓

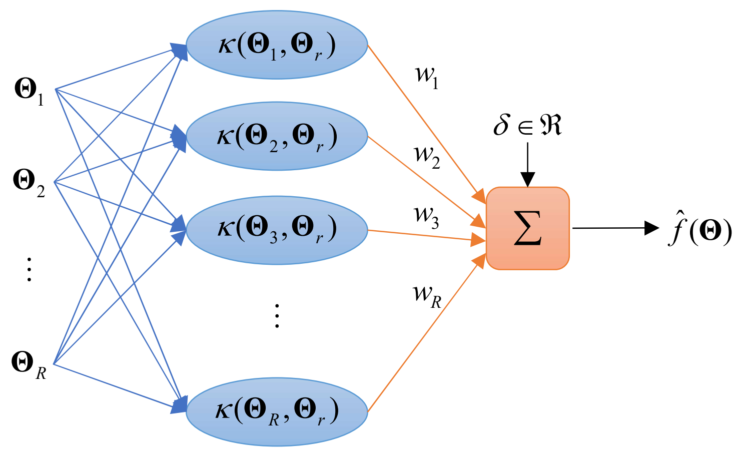
Machine learning aided approach

UNSW SYDNEY

❖ Efficient uncertainty analysis

➢ eXtended Support Vector Regression, i.e., X-SVR

This method is developed based on the theory of doubly regularised support vector machine (DrSVM). The idea of binary classification is extended here to regression, hence extended support vector regression (X-SVR).



The structure of the nonlinear X-SVR

Yu Y, Wu D, Wang Q, Chen X, Gao W. Machine learning aided durability and safety analyses on cementitious composites and structures. Int J Mech Sci 2019; 160: 165-81.
Yu Y, Wu D, Gao W. Stochastic chemo-physical-mechanical degradation analysis on hydrated cement under acidic environments. Appl Math Model 2020; 78: 75-97.

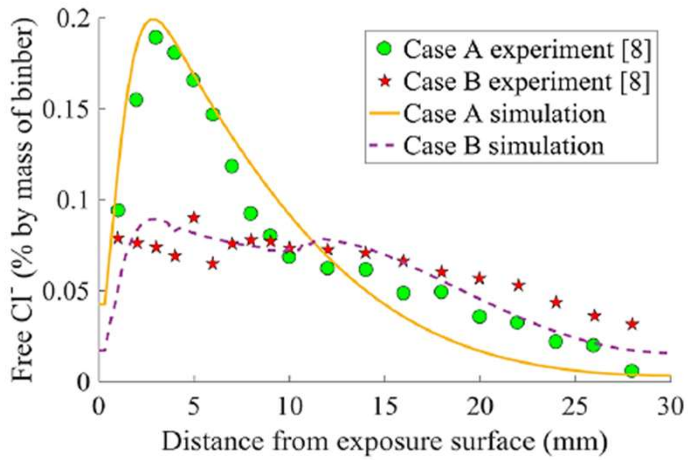
- **Application showcases**

❖ Application I: Multi-aging analysis (leaching + carbonation + chloride ingress)

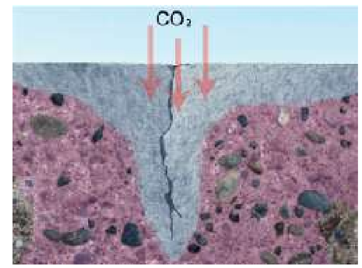
- Common durability concern for coastal infrastructures in contact with atmospheric marine environment

Case A: Without simultaneous carbonation

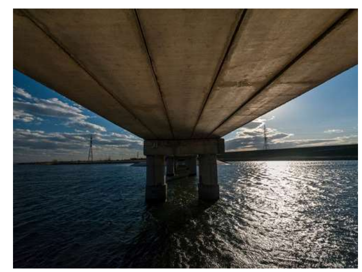
Case B: With simultaneous carbonation



Leaching



Carbonation

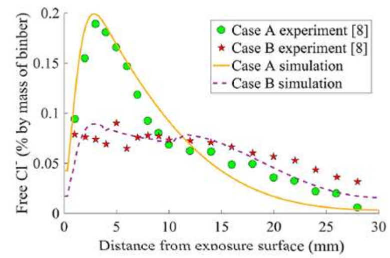


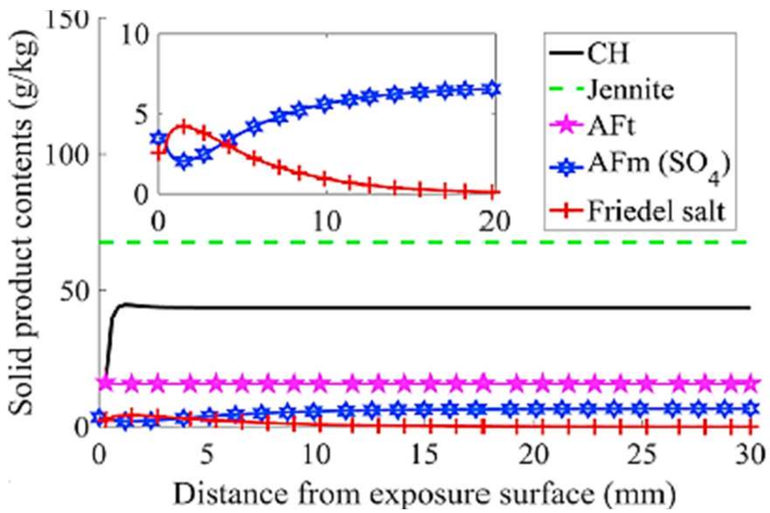
Chloride ingress

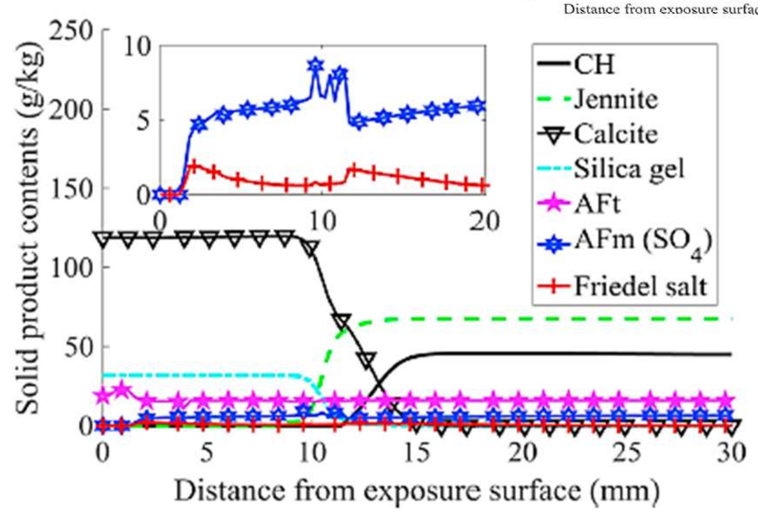
Yu Y, Chen X, Gao W, Wu D, Castel A. Impact of atmospheric marine environment on cementitious materials. Corros Sci 2019; 148: 366-78.

❖ Application I: Multi-aging analysis (leaching + carbonation + chloride ingress)

- Common durability concern for coastal infrastructures in contact with atmospheric environment







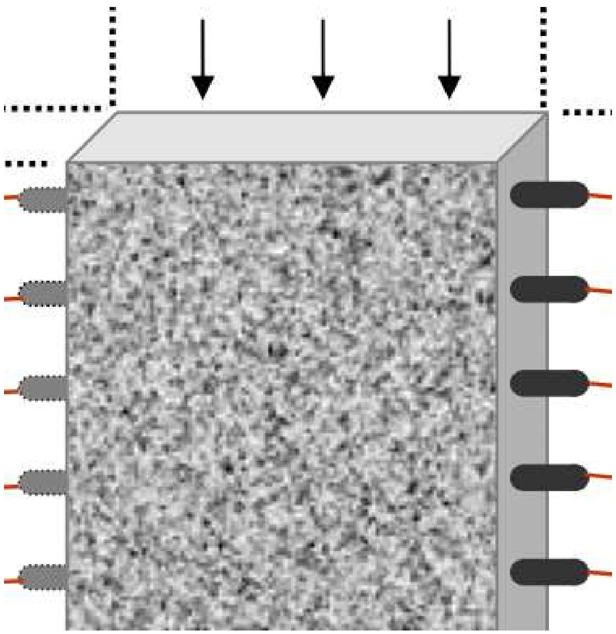
Case A: Without carbonation

Case B: With carbonation

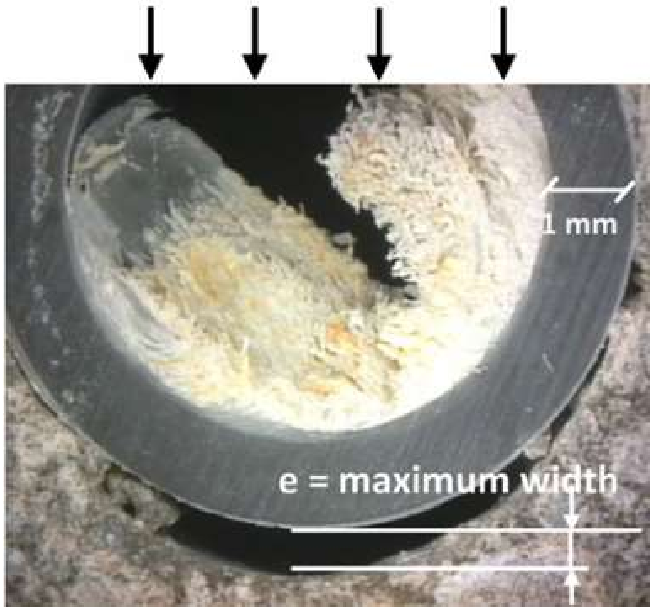
Yu Y, Chen X, Gao W, Wu D, Castel A. Impact of atmospheric marine environment on cementitious materials. Corros Sci 2019; 148: 366-78.

❖ Application II: Carbonation-induced aging corrosion with structural defect

Casting direction

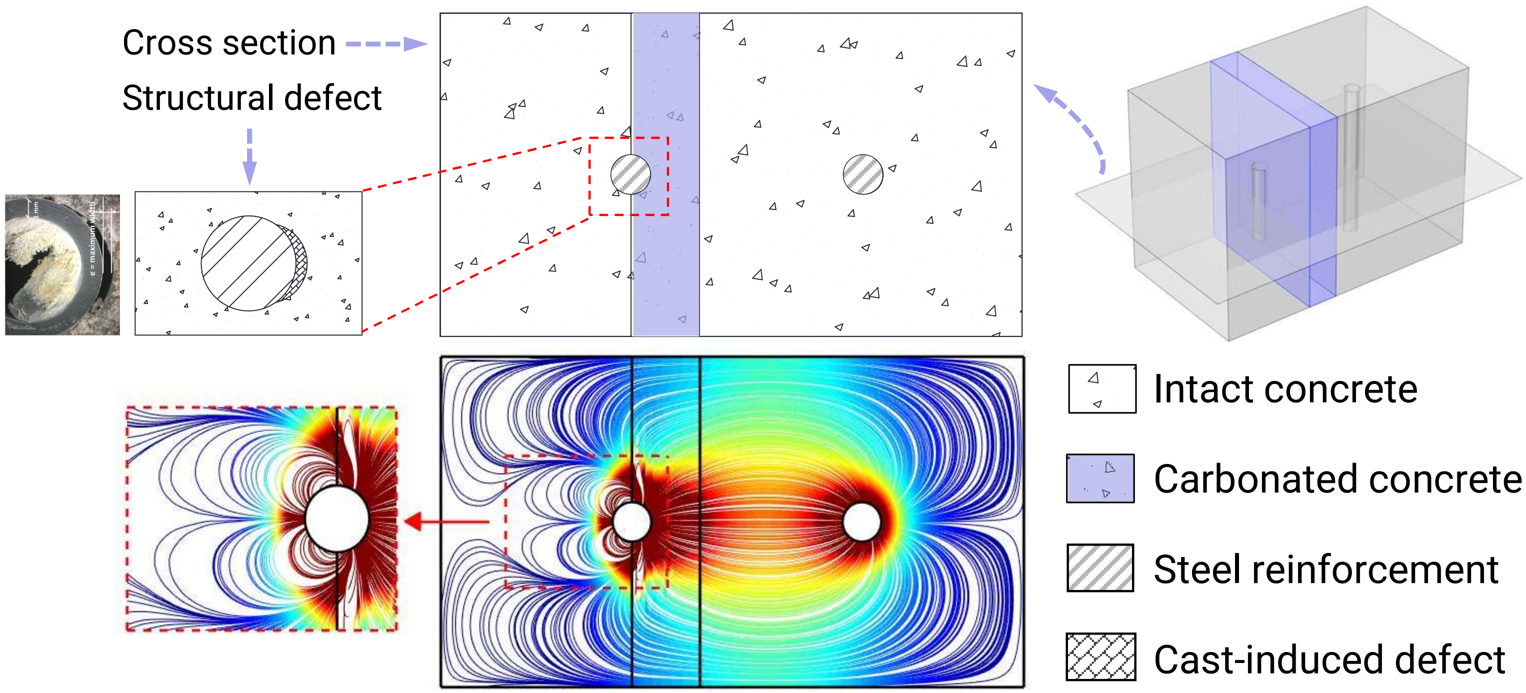


Casting direction



Common structural defect formed during construction

❖ Application II: Carbonation-induced aging corrosion with structural defect



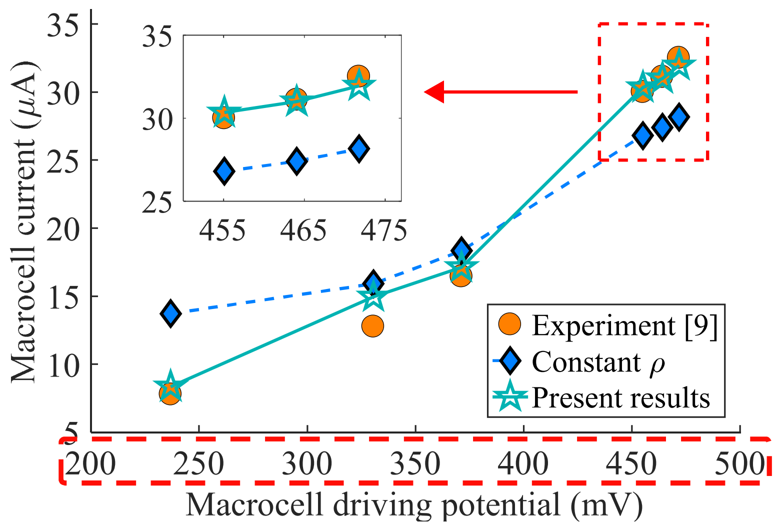
Corrosion current density streamline caused by localised carbonation and structural defect

Yu Y, Gao W, Castel A, Liu A, Feng Y, Chen X, Mukherjee A. Modelling steel corrosion under concrete non-uniformity and structural defects. Cem Concr Res 2020; 135: 106109.

❖ Application II: Carbonation-induced aging corrosion with structural defect

Different driving Potential caused by various extent of structural defect

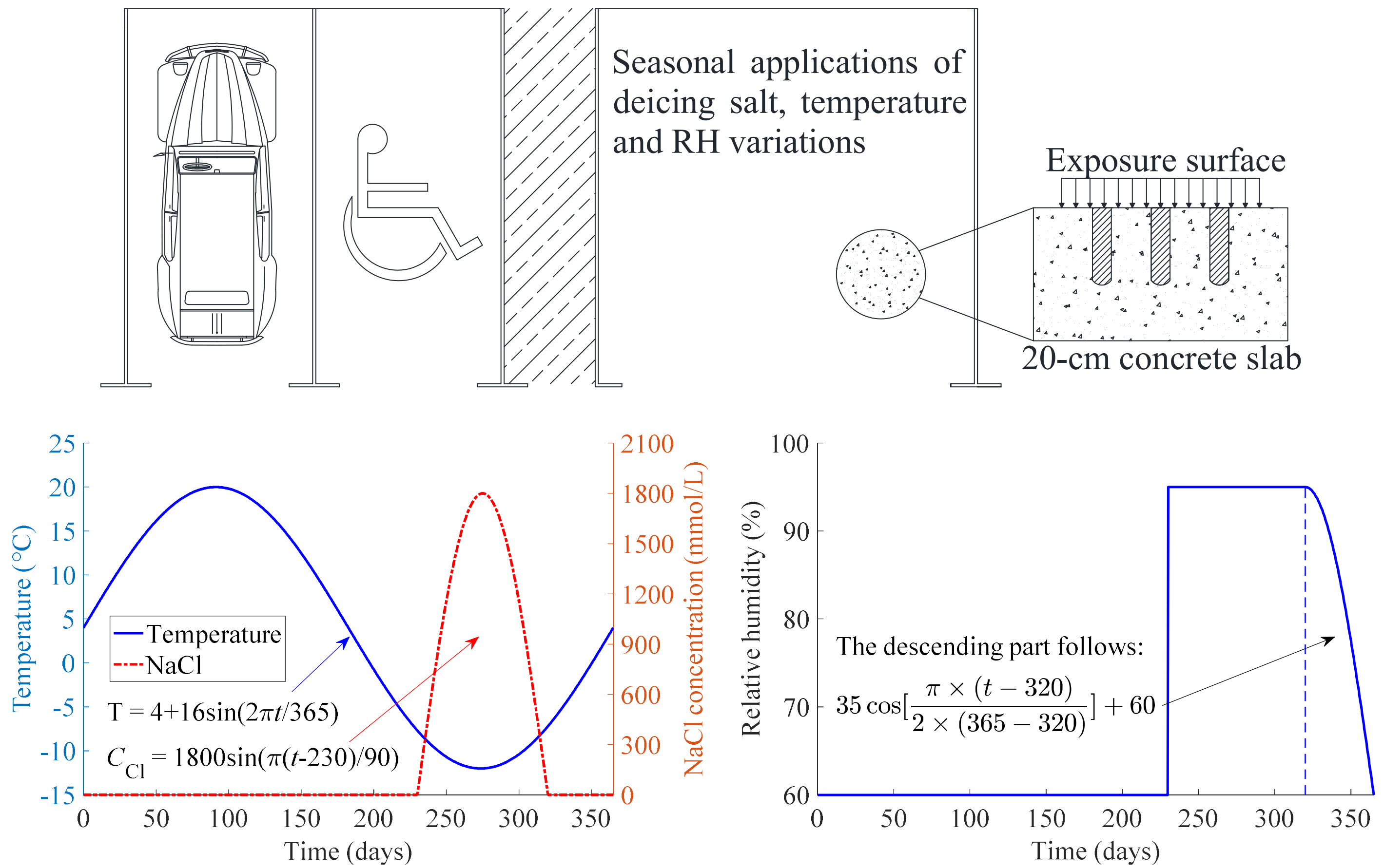
Set	Interfacial condition	Active steel	Passive steel	Driving potential ΔE (mV/SCE)
1	No defect	N3A	N9C	237.2
2	No defect	N1A	N4C	330.8
3	No defect	N2A	N5C	371.4
4	Defect	D2A	N7C	454.9
5	Defect	D3A	N6C	463.1
6	Defect	D1A	N8C	472.3



Yu Y, Gao W, Castel A, Liu A, Feng Y, Chen X, Mukherjee A. Modelling steel corrosion under concrete non-uniformity and structural defects. Cem Concr Res 2020; 135: 106109.

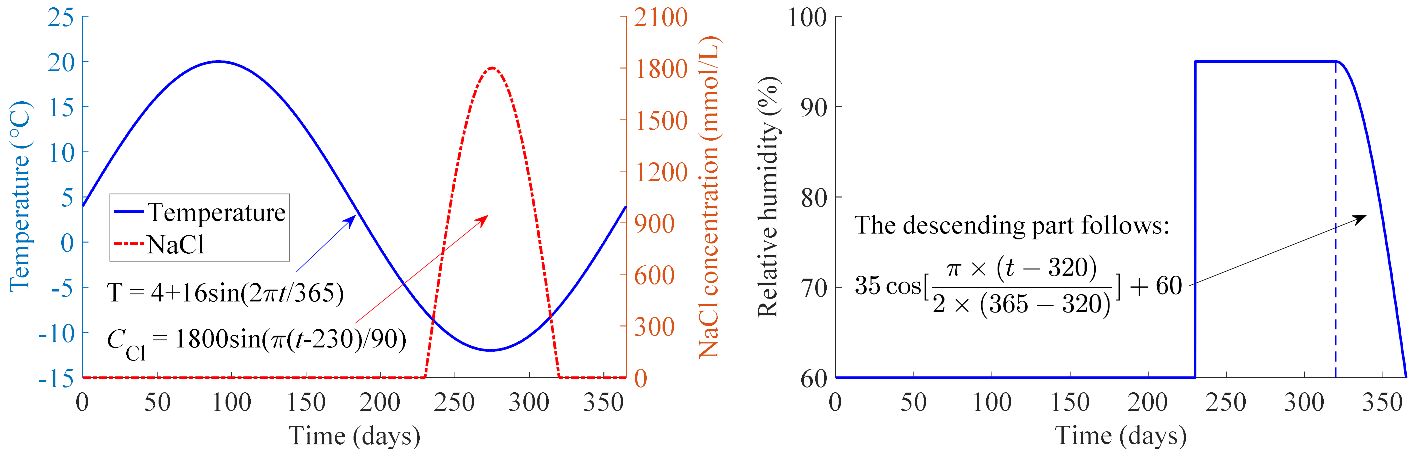
UNSW SYDNEY

❖ Application III: Stochastic chloride ingress under environmental uncertainty



Yu Y, Wu D, Wang Q, Chen X, Gao W. Machine learning aided durability and safety analyses on cementitious composites and structures. Int J Mech Sci 2019; 160: 165-81.

❖ Application III: Stochastic chloride ingress under environmental uncertainty

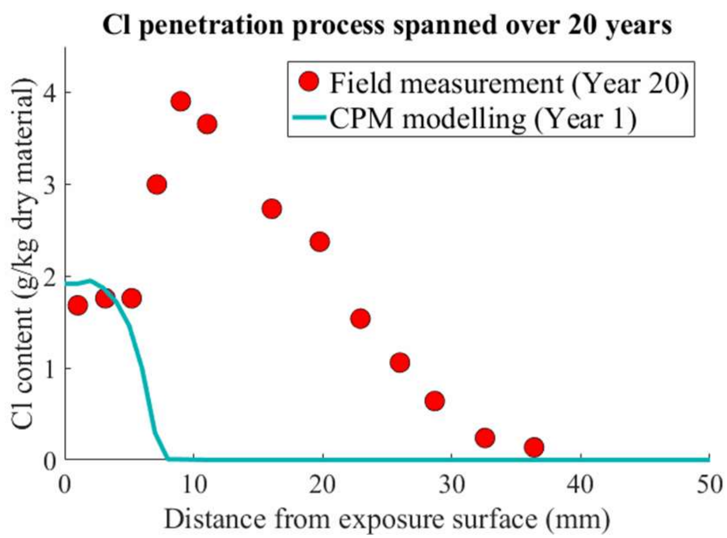


Random environmental parameters for stochastic chloride ingress analysis

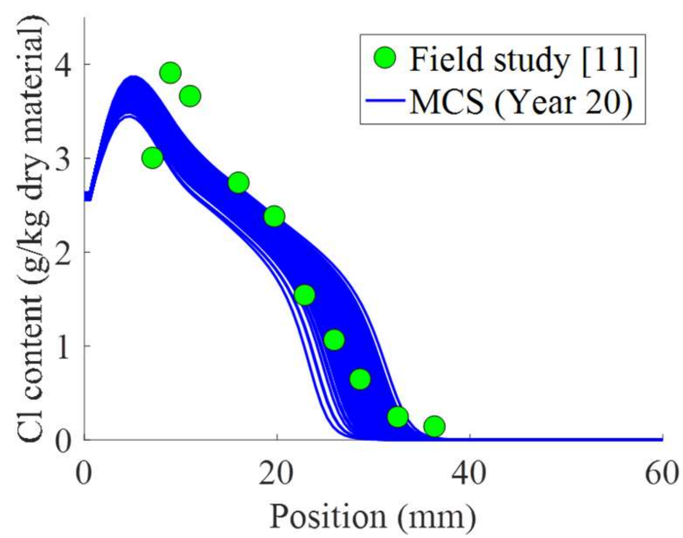
Variables	Mean	COV	Distribution type
RH^{R}_{ave}	60%	0.03	Lognormal
T^{R}_{ave}	$4\,^{\circ}C$	0.05	Normal
$C^{R}_{\mathrm{Cl_{max}}}$	1800 mmol/L	0.056	Uniform

Yu Y, Wu D, Wang Q, Chen X, Gao W. Machine learning aided durability and safety analyses on cementitious composites and structures. Int J Mech Sci 2019; 160: 165-81.

❖ Application III: Stochastic chloride ingress under environmental uncertainty



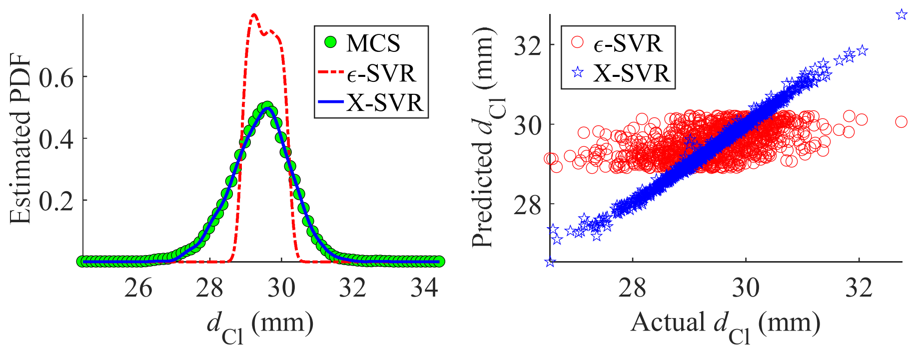
<u>Deterministic</u> solution throughout 20-year service duration



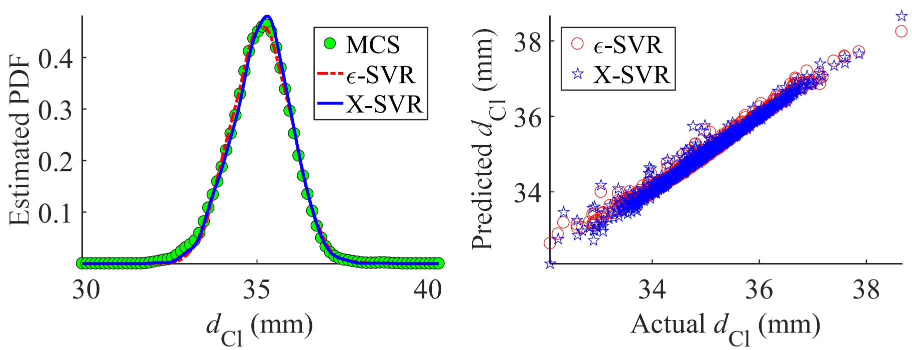
<u>Stochastic</u> solution through Monte Carlo Simulation of 10^6 function evaluations

Yu Y, Wu D, Wang Q, Chen X, Gao W. Machine learning aided durability and safety analyses on cementitious composites and structures. Int J Mech Sci 2019; 160: 165-81.

❖ Application III: Stochastic chloride ingress under environmental uncertainty



chloride ingress depth at ***Year 15***: (left) response PDF plot; (right) response scatter plot



chloride ingress depth at ***Year 20***: (left) response PDF plot; (right) response scatter plot

Comparisons of response statistics on ingress depth

Response	N_{fun}	Mean (mm)			Standard deviation		
		MCS	ε-SVR	X-SVR	MCS	ε-SVR	X-SVR
Year 5	20		13.5068	**13.5842**		0.2152	**0.6209**
	40		13.4832	**13.5642**		0.0069	**0.6457**
	60	13.5543	13.5494	**13.5532**	0.6627	0.6537	**0.6657**
	80		13.5501	**13.5518**		0.2287	**0.6607**
	100		**13.5551**	13.5595		0.6662	**0.6602**
Year 10	20		22.5013	**22.4142**		0.5026	**0.8016**
	40		22.4684	**22.4320**		0.0314	**0.8124**
	60	22.4138	22.4505	**22.4235**	0.8352	0.7965	**0.8241**
	80		22.4370	**22.4177**		0.8282	**0.8294**
	100		22.4361	**22.4233**		0.7970	**0.8080**
Year 15	20		29.4486	**29.4307**		0.7913	**0.8037**
	40		29.4473	**29.4425**		0	**0.7866**
	60	29.4320	29.4138	**29.4389**	0.8318	**0.8317**	0.8125
	80		29.4524	**29.4416**		0.7918	**0.8041**
	100		29.4444	**29.4413**		0.8014	**0.8114**
Year 20	20		35.0904	**35.1929**		0.3872	**0.8351**
	40		35.1365	**35.1044**		0.0497	**0.8338**
	60	35.1050	**35.1332**	35.1366	0.8688	0.8303	**0.8408**
	80		35.1156	**35.1078**		0.6203	**0.8699**
	100		35.1173	**35.1092**		0.8333	**0.8657**

Concluding remarks:

Despite the irreplaceable role in modern structural health monitoring, physical corrosion monitoring has its own *limitation*. In this regard, a comprehensive virtual monitoring may be crucial in greatly *supplementing* the physical counterpart, and the proposed CPM-EC algorithm, combining with novel machine learning technique, is poised to be a promising candidate with demonstrated capability of *efficiently* generating *accurate and diagnostic predictions*.