Deterioration/Damage Process
Spatial and Temporal Variability

- Most analyses assume homogeneous material, dimensional and environmental properties
    - e.g., concrete surface is either
        - (i) perfect or (ii) completely cracked/spalled
    - rust stains, cracking not homogeneous across concrete surface
    - e.g., rebar corrosion is never uniform
  - not realistic!

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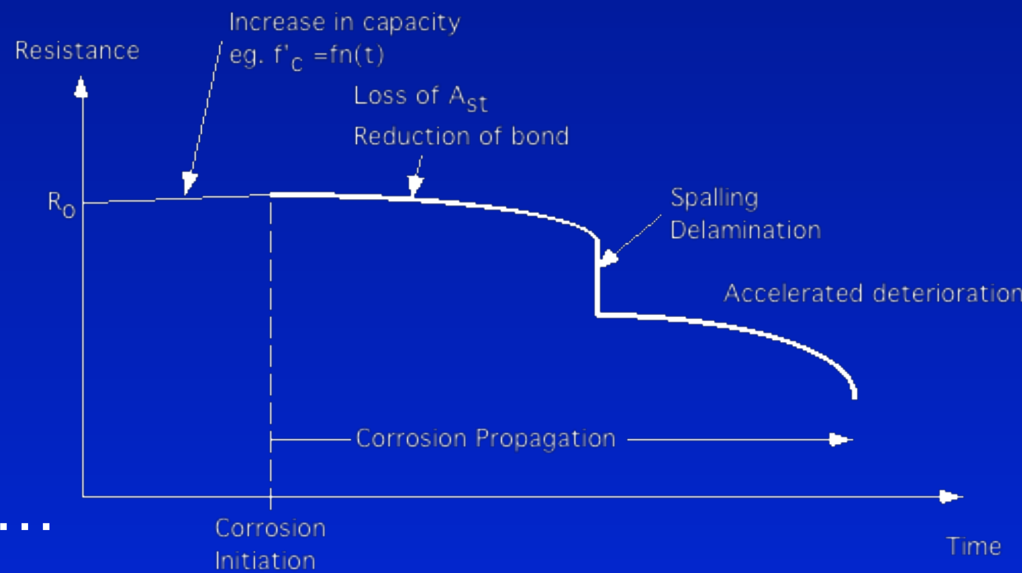
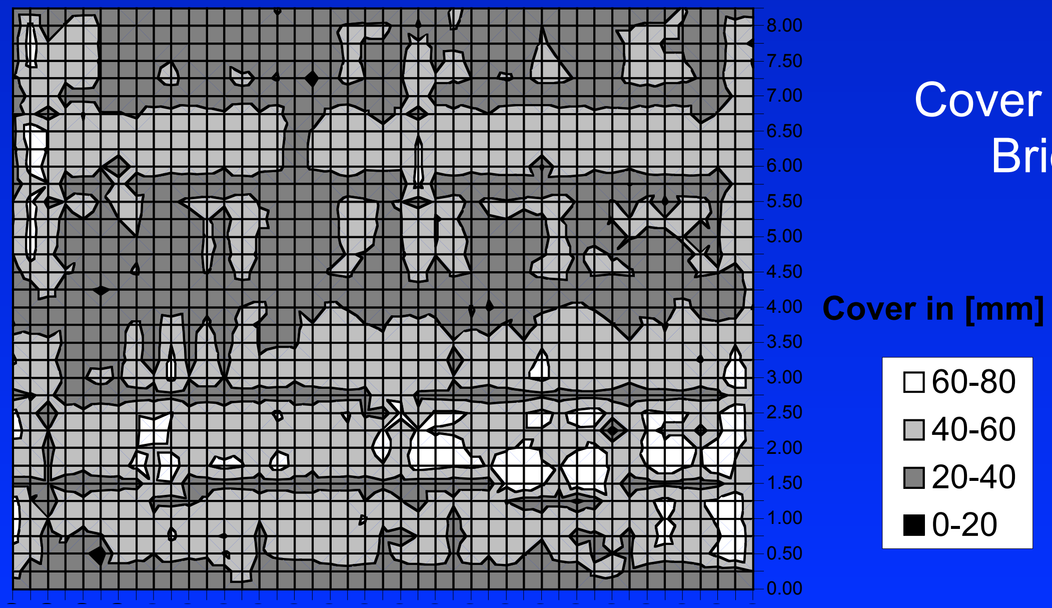
… Deterioration/Damage

- highly localised
  - spatially distributed
- time-dependent
- 'hidden'
- concrete, steel, timber, …





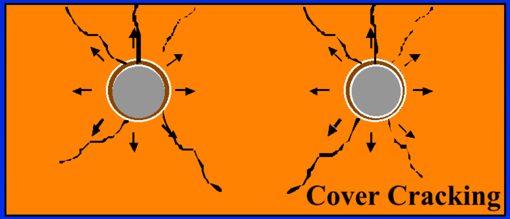
Cover Variability for Bridge Deck

Corrosion Damage

(Stewart & Mullard 2007, 2009, 2011)

- Corrosion Damage
  - corrosion-induced cracking of concrete cover
    - crack Initiation
    - crack propagation
      - w/c ratio and cover are important factors
      - corrosion rate reduces with time (e.g., due to the formation of corrosion products on the steel surface)

- Need to predict likelihood and extent of damage



  - *Random field modelling of deterioration*
  - *Spatial time-dependent reliability analysis*

Spatial Time-Dependent Reliability Analysis

- 2D Random Field
- Typical spatial variables:
  - concrete quality and cover
    - caused by different concrete batches and variability of workmanship
  - exposure to aggressive agents (chlorides)
    - caused by different exposure conditions (e.g., sheltered, not sheltered, or splash areas)
  - Corrosion initiation and propagation are spatially variable

- Need to model complex time-dependent interactions
  - subject to high uncertainty when predicting over many years
  - need new or updated information!

... Spatial Time-Dependent Reliability Analysis

(Stewart & Mullard 2007, 2009)

- Predict *two* measures of performance
  - Prior distributions (no inspection data)
    - 1. Proportion of a concrete surface subject to cracking

$$d_{crack}(t) = \frac{n\left[t > T_{i(j)} + T_{sp(j)}\right]}{k} \times 100\%$$

  - $T_{i(j)}$ = time to corrosion initiation of element j
  - $T_{sp(j)}$ = time to excessive cracking of element j
  - k = number of elements

- Monte-Carlo simulation analysis
  - distribution of $d_{crack}(t)$

$$f_{d_{crack}}\left(d_{crack}, t\right)$$

- 2. Probability that at least x% of a concrete surface has cracked

$$\Pr\left(d_{crack}(t) \geq x\%\right) = \int_{x\%}^{100\%} f_{d_{crack}}\left(d_{crack}, t\right)\, dd_{crack}$$

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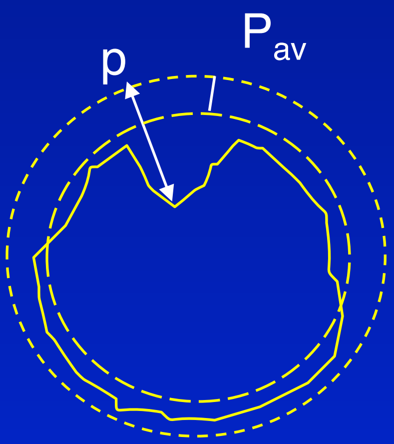
Reliability of RC Beams with Pitting Corrosion

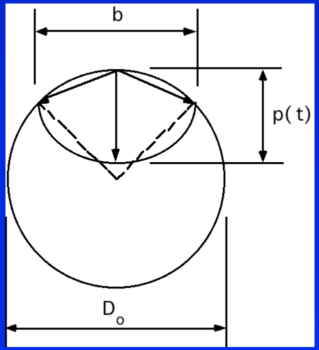
(Stewart 2004, 2009, 2011)



- Pitting factor $R=p/P_{av}$
- Max R for rebar of length L_U
  - R increases as L_U increases
  - R obtained from accelerated corrosion tests
    - Indicative only…
    - Many problems obtaining such data from real structures
  - Gumbel distribution

$$\mu = \mu_o + \frac{1}{\alpha_o}\ln\left(\frac{L_U}{L_o}\right)$$

$$\alpha = \alpha_o$$



Specimen	L_o (mm)	Diameter (mm)	Pitting Factor R		Gumbel Parameters	
			mean	COV	μ_o	α_o
Y10	100	10	5.65	0.22	5.08	1.02
Y16	100	16	6.2	0.18	5.56	1.16
Y27	100	27	7.1	0.17	6.55	1.07

$$p(t) = 0.0116 \times i_{corr} \times R \times t$$

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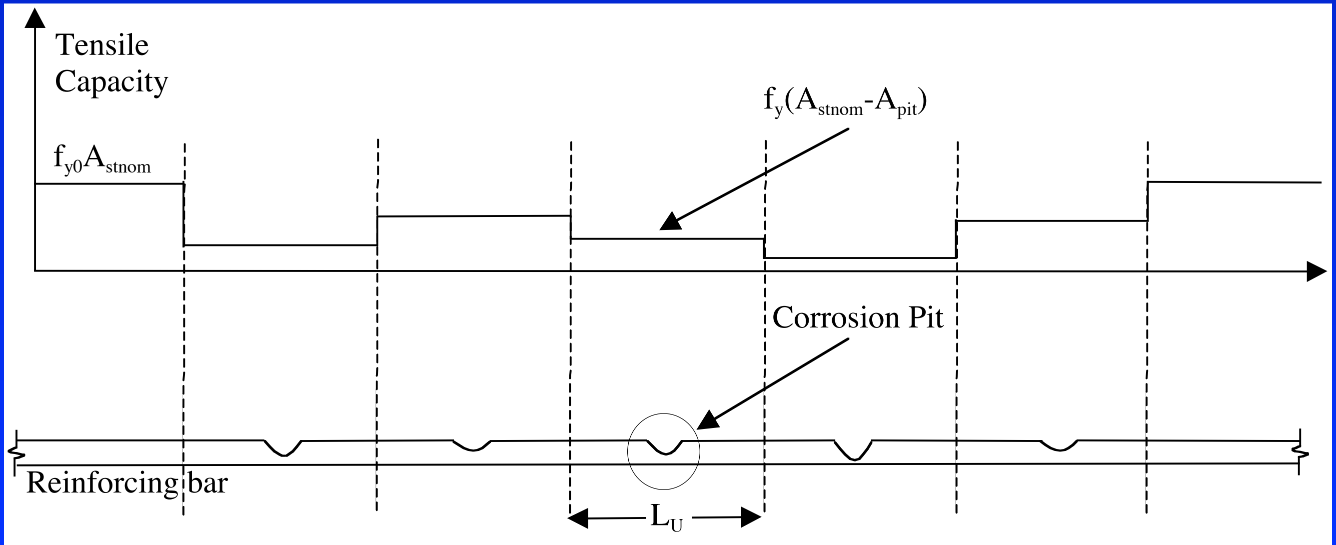
… Reliability of RC Beams with Pitting Corrosion

- Corrosion loss $Q_{corr}=A_{pit}/A_{nom}x100\%$
- Ductile ⟹ Brittle as corrosion increases
  - Ductile behaviour: $Q_{corr}<20\%$
  - Brittle behaviour: $Q_{corr}>20\%$
- Assume loss of capacity occurs over length L_U
  - L_U=500 mm



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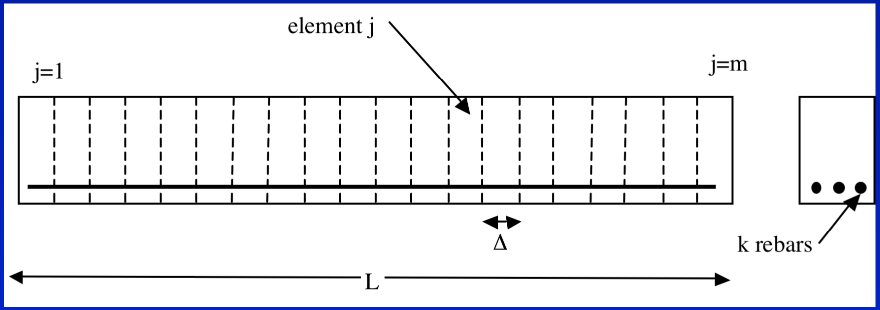
… Reliability of RC Beams with Pitting Corrosion

- Discretisation of RC beam



  - critical flexure limit state

$$G_{M,t_i}(X) = \min_{j=1,N_M}\left(M_j(t_i) - S_j(t_i)\right)$$

    - S_j=bending moment at mid-point of each element
    - M_j = flexural resistance

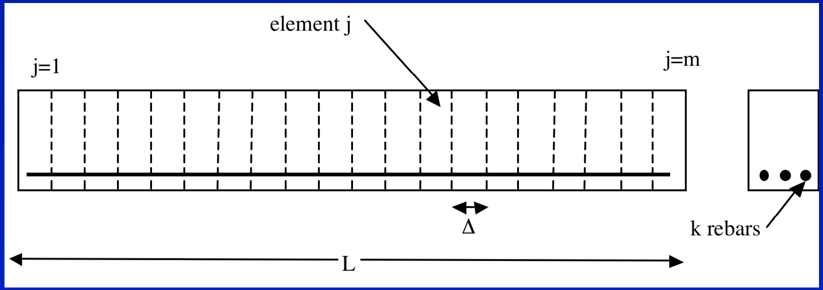
  - cumulative probability of failure

$$p_f(0,t) = 1 - \Pr\left[G_{M,t_t}(X) > 0 \cap G_{M,t_2}(X) > 0 \cap .....\cap G_{M,t_K}(X) > 0\right]$$

    - K annual load events

Example Application: RC Bridge Deck

- RC beam
  - simply supported
  - L = 10 m
  - 400 mm x 900 mm cross-section
    - n_M=6 main rebars (Y27)
    - element length Δ=L_U=500 mm
    - N = 20 elements



- Corrosion occurs from exposure to coastal sea-spray
- Damage limit state (1 mm crack width)
- 1D random field:
  - concrete cover
  - concrete compressive strength
  - surface chloride concentration
  - pit depth

Corrosion initiation and propagation are spatially variable

- Monte-Carlo methods

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- Statistical parameters

Parameter	Mean	COV
C_o (surface Cl concentration)	3.05 kg/m^3	0.74
C_r (threshold Cl concentration)	2.4 kg/m^3	0.2
Model errors for D and i_{corr}	1.0	0.2
Model error: $t_{sp}(w_{\lim} = 0.3\text{ mm})$	1.09	0.19
$t_{sp}(w_{\lim} = 1.0\text{ mm})$	1.05	0.20
Model error: Flexural capacity	1.02	0.06
Shear capacity	1.075	0.10
Cover	+1.6 mm	$\sigma = 11.1$ mm
Reinforcement yield strength f_{y0}	467.5 MPa	0.03
Concrete cylinder strength f'_{cyl}	$F'_c + 7.4$ MPa	$\sigma = 6$ MPa
k_w ($f'_c = k_w f'_{cyl}$)	0.87	0.06
Concrete tensile strength f'_{ct}	$0.53\ (f'_c)^{0.5}$	0.13
Concrete elastic modulus E'_c	$4600\ (f'_c)^{0.5}$	0.12

very high uncertainties with
deterioration model and parameter estimates

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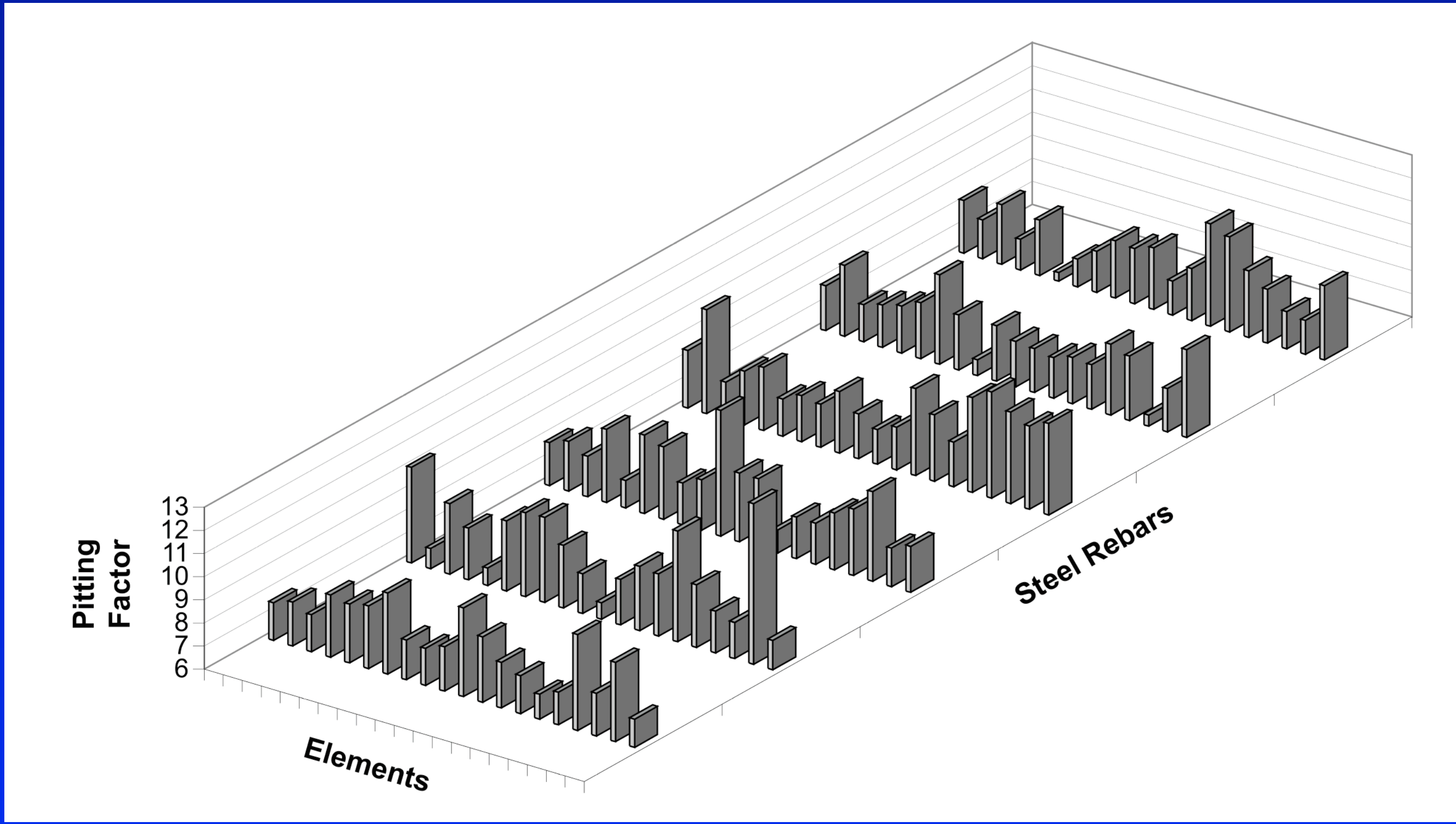
Spatial Variability of Pitting Along a Rebar
(typical Monte-Carlo realisation)



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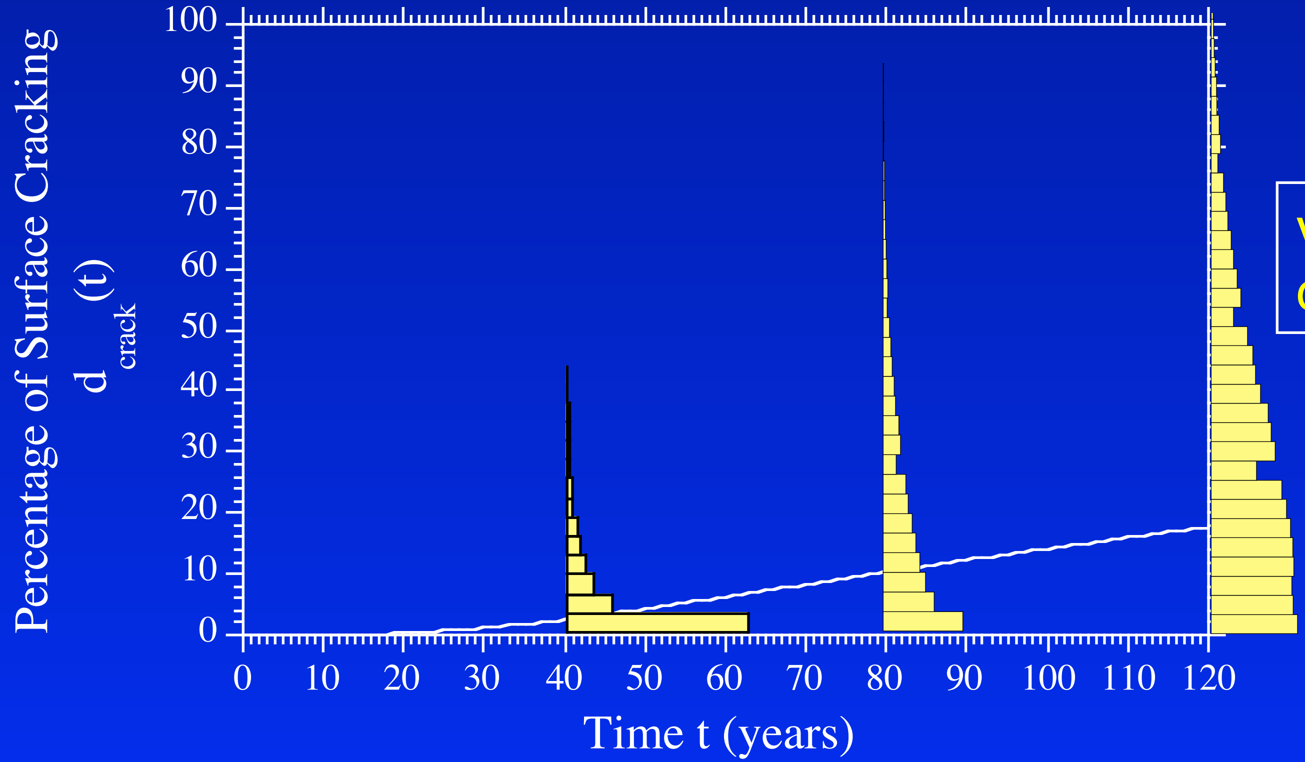
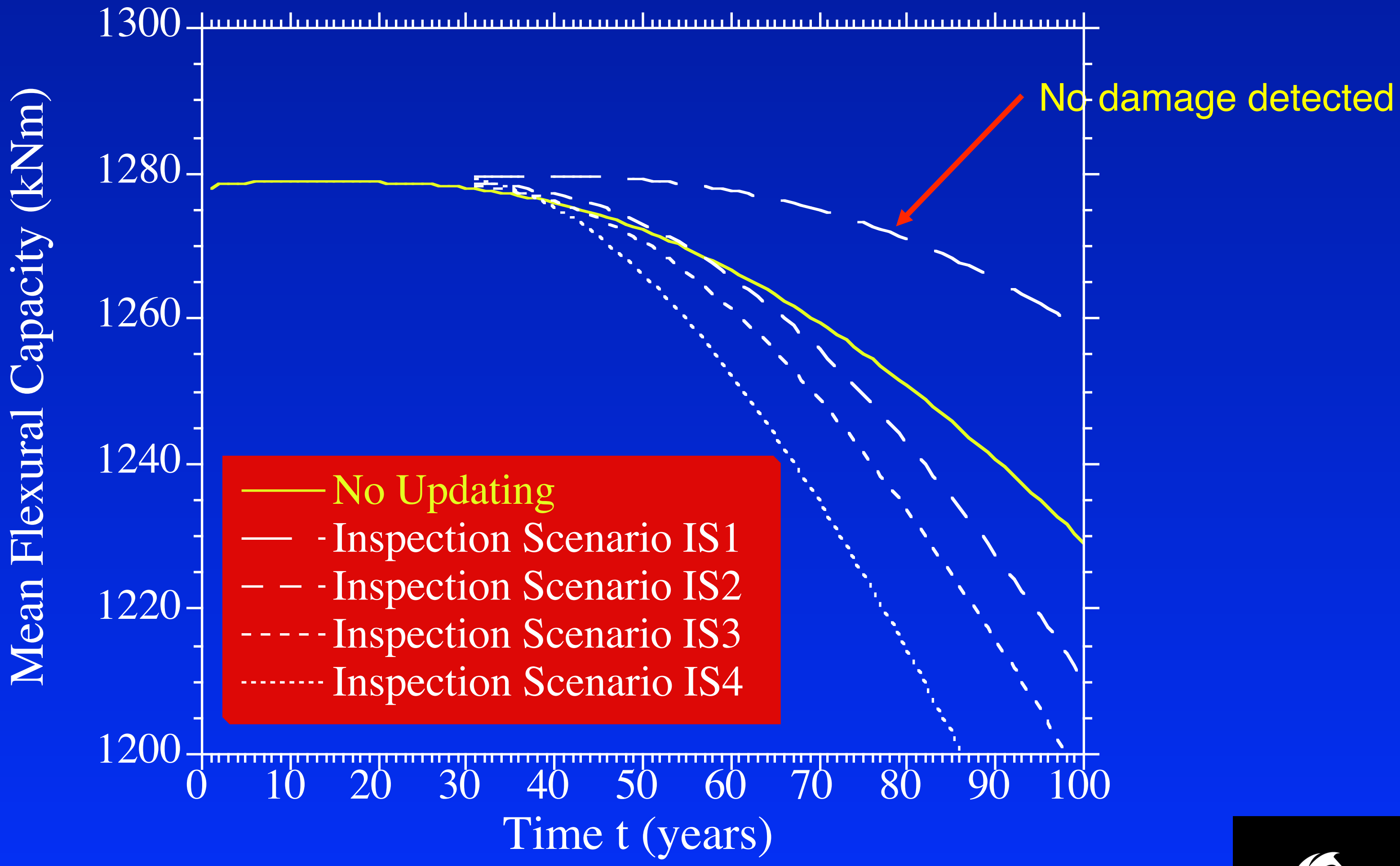
... Results
Mean Proportion of Corrosion Damage $d_{crack}(t)$



variability of $d_{crack}(t)$

… Results
Mean of Resistance



Life-Cycle Costs (LCC)

- Total life-cycle cost:

$$LCC(T) = C_D + C_C + C_{QA} + C_{IN}(T) + E_{SF}(T)$$

Expected damage costs

$$E_{SF}(T) = \sum_{i=1}^{T/\Delta t} \Delta P_{f,i} \frac{C_{repair}}{(1+r)^{i\Delta t}}$$

Pr(damage exceeds repair threshold X_{repair})

$$\Delta P_{f,i} = \Pr\left(d_{crack}(t) \geq X_{repair} \middle| d_{crack}(t-\Delta t) < X_{repair}\right)$$

ALL results stem from knowing likelihood and extent of damage $d_{crack}(t)$

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Maintenance Strategy
Patch Repairs

- Repair threshold (X_{repair})
  - Proportion of damage before repair
    - Delayed repairs v increased repair area
- Inspection Interval (Dt)
  - Regularity of inspection
    - Reduced inspection costs v possible large repair area
- Efficiency of repair
  - Corrosion initiation (D_{Ti})
    - Improved permeability, incomplete chloride removal
  - Corrosion rate (γ_{Icorr})
    - Corrosion inhibitors, incipient anodes

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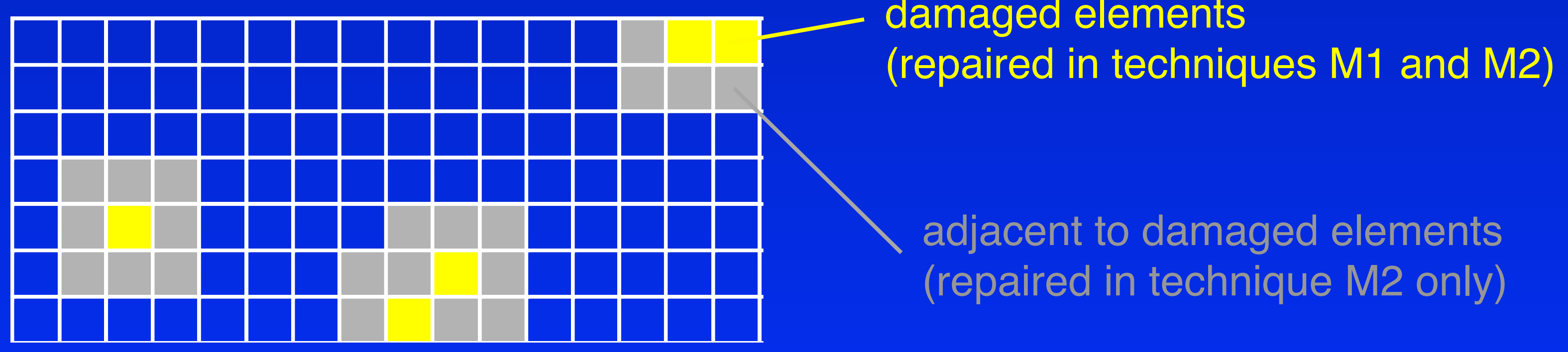
… Maintenance Strategy

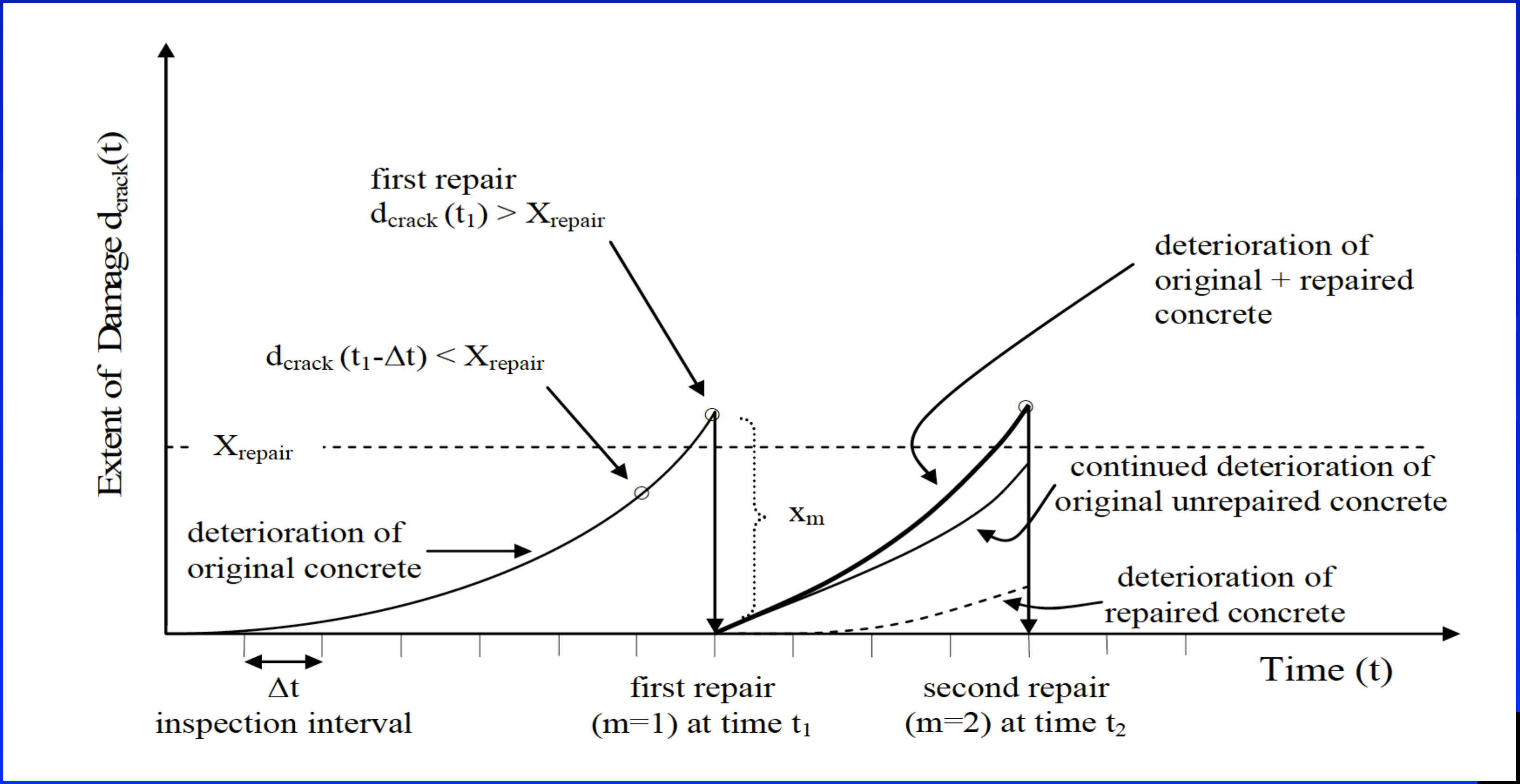
- Repair techniques
  - M1 - Patch repair
    - Repairs the damage area only
  - M2 - Preventative patch repair
    - Repairs area adjacent to damaged area also



- M3 - Complete rehabilitative overlay
  - Removal and replacement of the entire RC surface over the reinforcing bars

… Maintenance Strategy

- M1



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… Maintenance Strategy

Repair Efficiency

Repair Durability Specification	Δ_{Ti} (years)	γ_{icorr} (%)
Baseline case (patch repair same as original construction)	0	0
Concrete surface treatment	15	0
Corrosion inhibitor	7	-50
Cathodic Protection[#]	0	-100

Increased time to corrosion initiation

reduced **corrosion** rate

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Summary of Maintenance Options

Maintenance strategy	Inspection interval Δt	Repair threshold (X_{repair})	Maintenance technique	Repair method	Repair Cost	User Delay	Repair efficiency	
							Δ_{Ti} (years)	γ_{icorr} (%)
1	1 year	2 %	M1	None	$440/m^2	$61,000	0	0
2	1 year	2 %	M2	None	$440/m^2	$122,000	0	0
3	1 year	12 %	M3	None	$440/m^2	$1.9 million	0	0
4	1 year	2 %	M1	Silane	$461/m^2	$61,000	15	0
5	1 year	2 %	M2	Silane	$461/m^2	$122,000	15	0
6	1 year	12 %	M3	Silane	$461/m^2	$1.9 million	15	0
7	1 year	2 %	M1	Corrosion Inhibitor	$458/m^2	$61,000	7	-50
8	1 year	2 %	M2	Corrosion Inhibitor	$458/m^2	$122,000	7	-50
9	1 year	12 %	M3	Corrosion Inhibitor	$458/m^2	$1.9 million	7	-50
10	1 year	12 %	M3	Cathodic Protection	$740/m^2	$1.9 million	0	-100#

Different Effectiveness
Different Costs
Different Times to Repair
????

LCC to assess optimal maintenance strategy

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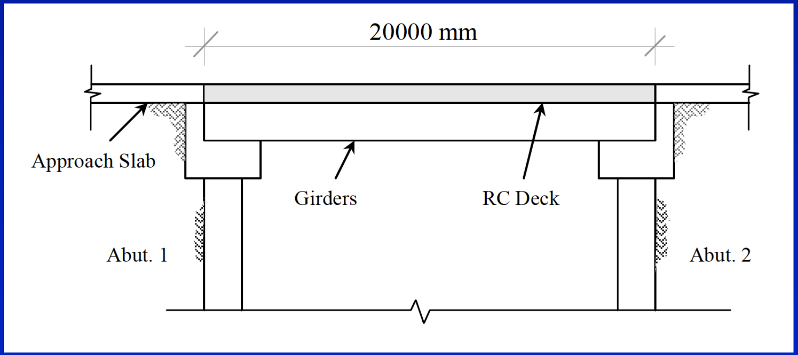
Example Application: RC Bridge Deck

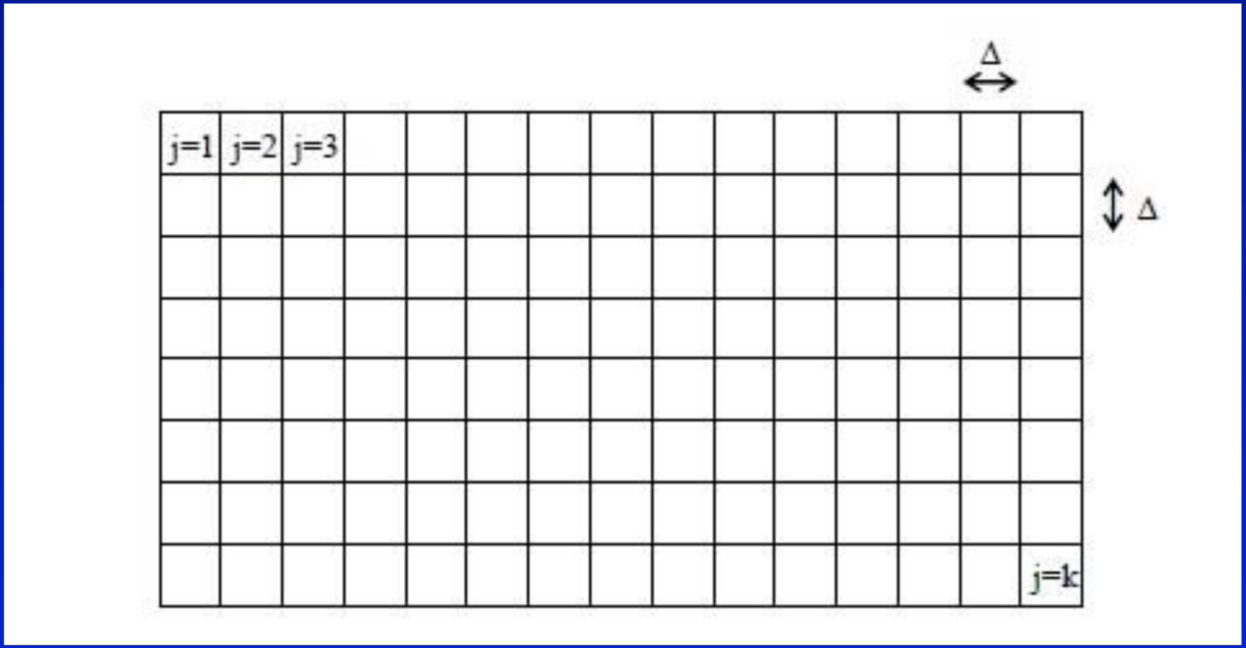
- RC bridge deck
  - A=400 m^2, Φ16 mm rebars
  - cover = 50 mm, F'_c = 40 MPa
  - 120 year service life



- Corrosion occurs from exposure to coastal sea-spray
- Damage limit state (1 mm crack width)
- 2D random field:
  - Element size = 0.25 m^2, number of elements = 1,600
- Spatial variability:
  - concrete cover
  - concrete compressive strength
  - surface chloride concentration

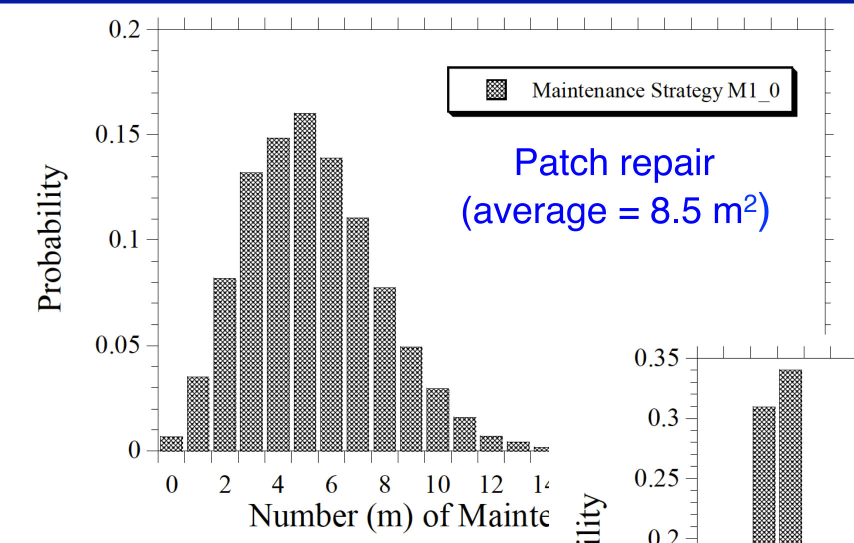
Corrosion initiation and propagation are spatially variable

- Monte-Carlo methods

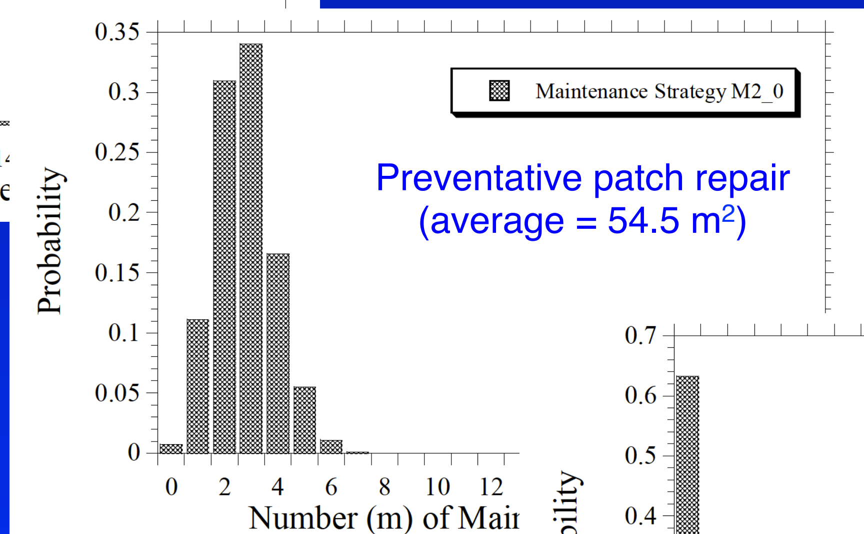


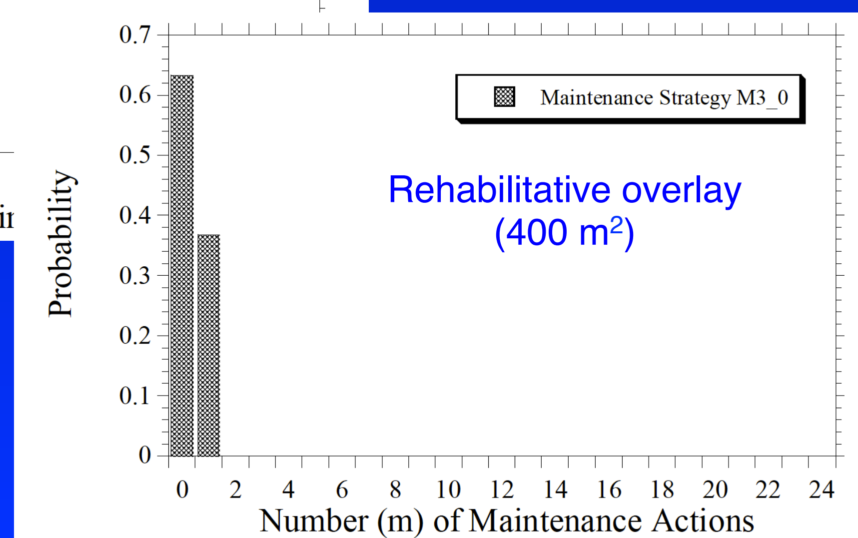
– element size = 0.5 x 0.5 m

Results
Number of Maintenance Actions



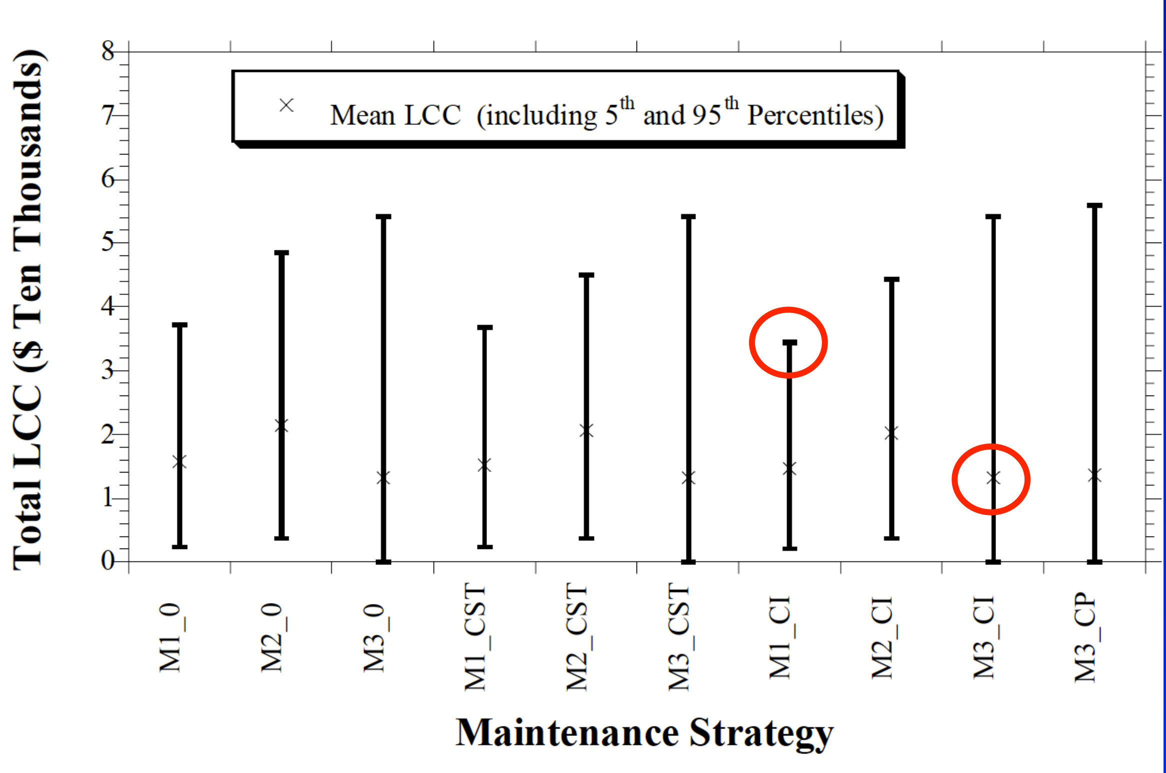
Large variability





… Results

LCC - 90% confidence interval



Single asset

= **risk averse** decision-maker
= more concerned about large costs (upper 95th percentile)

select M1_CI
(patch repair, corrosion inhibitor)

Many assets

= **risk neutral** decision-maker
large number of assets
use mean (expected values)

select M3_CI
(complete rehabilitative overlay, corrosion inhibitor)

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Table 2: Random field parameters[6].

Parameter	Mean	COV	Scale of fluctuation θ (m)	Distribution
Concrete cover	Tables 3 & 4	Table 3	2	Truncated normal
Concrete strength $f_c(28)$	Tables 3 & 4	Table 3	1	Truncated normal
Diffusion coefficient D_1	Table 4	σ=0.15	2	Lognormal
Binding capacity a	Eq.(3)	0.3	2	Lognormal

Table 3: Statistical parameters for corrosion parameters, material properties and dimensions.

Parameters	Mean	COV	Distribution	Reference
Concrete cover	C_{nom}[e] +6 mm	σ=11.5 mm	Truncated normal[a]	28
Compressive strength $f_c(28)$				
25	1.05F'c[f]	0.156	Truncated normal[b]	29
32	1.06F'c[f]	0.152	Truncated normal[b]	29
40	1.07F'c[f]	0.151	Truncated normal[b]	29
Tensile strength f_t	$0.53(f_c)^{0.5}$	0.13	Normal	30
Elastic modulus E_c	$4600(f_c)^{0.5}$	0.12	Normal	30
Age factor n_d	Table 4	0.12	Normal	3
Model error $ME(r_{crack})$	1.04	0.09	Normal	22
Thickness of pore zone δ_0	15 μm	0.1	Normal	3
Correction factor k_{site}				5
Urban area	1.14	0.08	Truncated normal[c]	5
Suburban area	1.07	0.06	Truncated normal[c]	5
Rural area	1.05	0.04	Truncated normal[c]	5
Corrosion rate $i_{corr(ref)}$	0.172 $\mu A/cm^2$	0.5	Lognormal[d]	14

Notes - [a]: truncated at 8 mm. [b]: truncated at 0 MPa. [c]: truncated at 1.0. [d]:1 $\mu A/cm^2$ = 0.0116 mm/year. [e]: C_{nom} is the nominal or design cover. [f]: F'_c is the nominal design concrete compressive strength.

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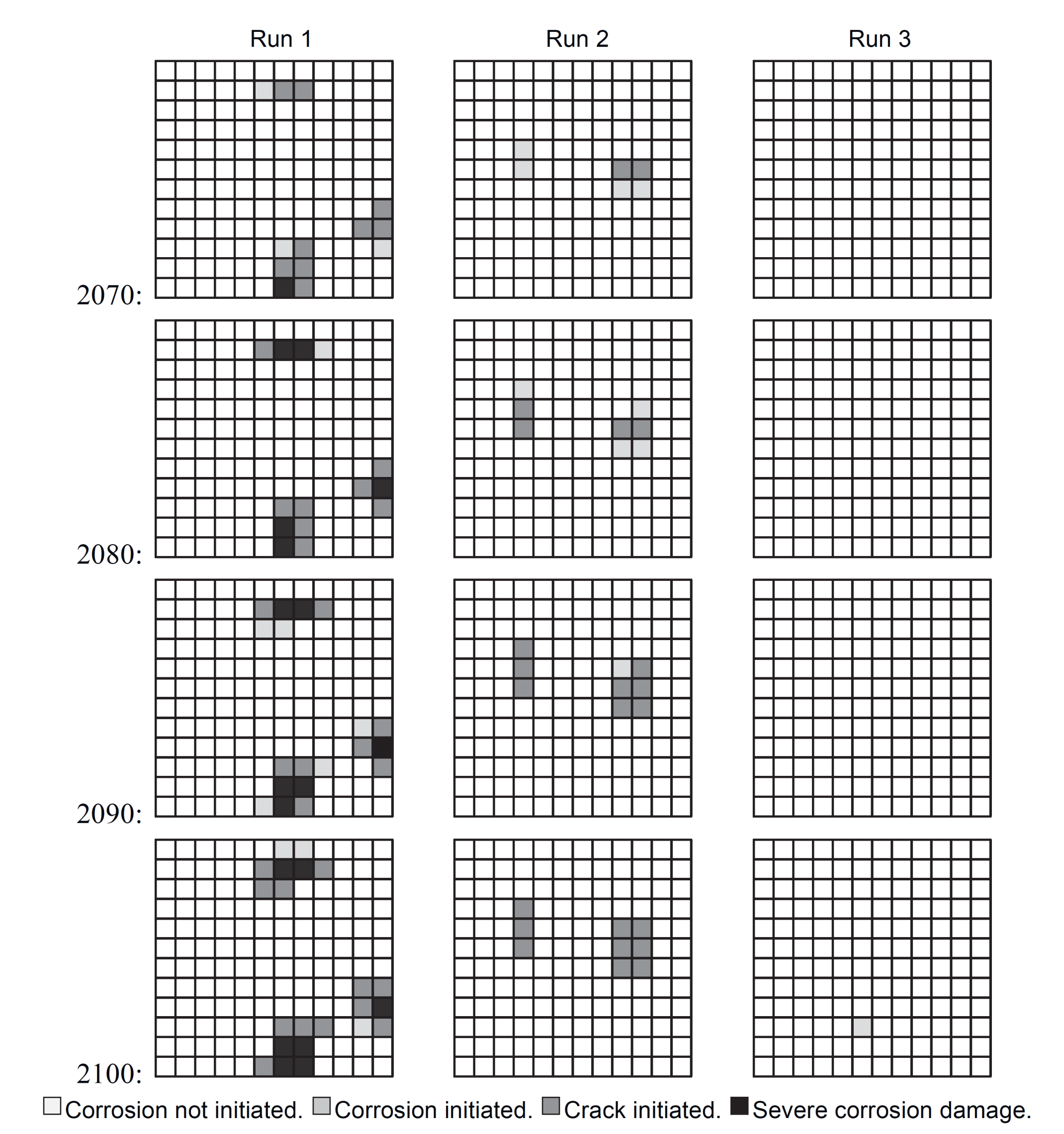
Sydney


Run 1
Run 2
Run 3
2070:
2080:
2090:
2100:
Corrosion not initiated.
Corrosion initiated.
Crack initiated.
Severe corrosion damage.

China

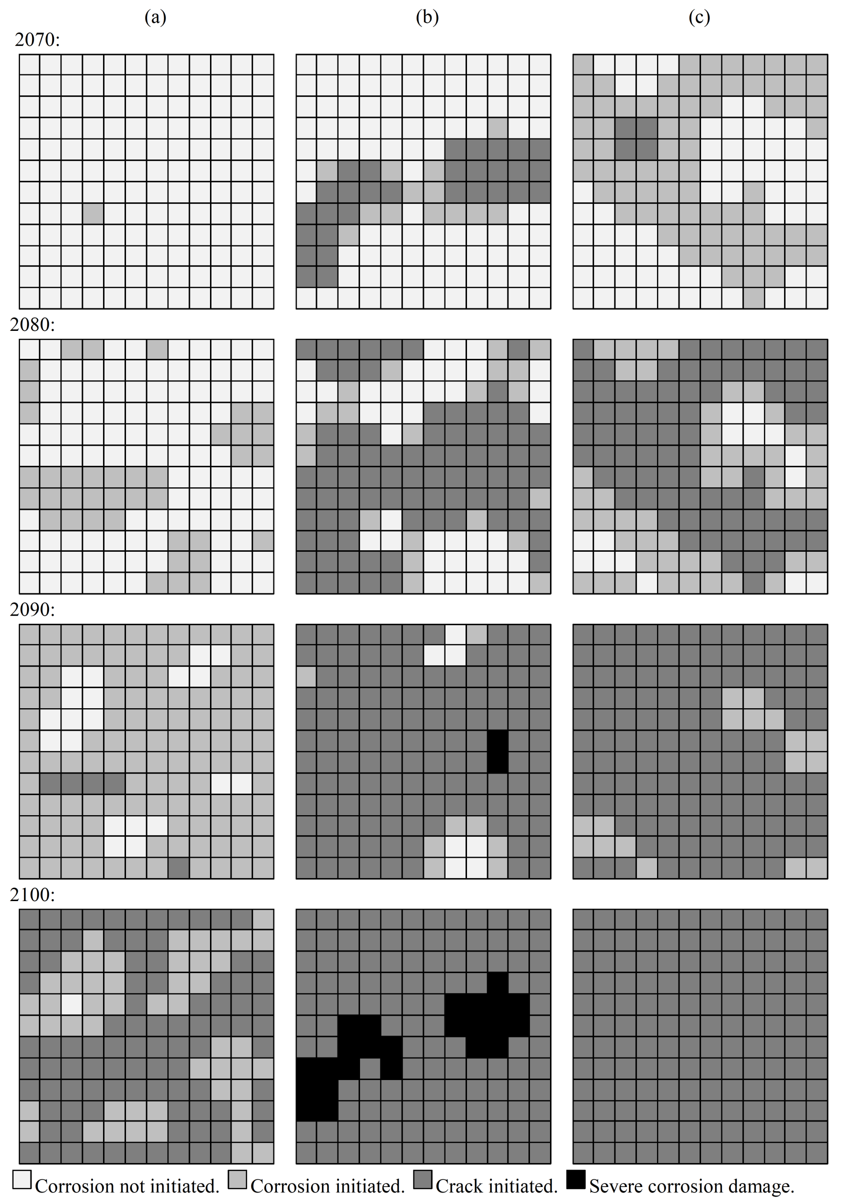


Figure 5-8. Simulation of spatially distributed corrosion process showing three typical Monte Carlo realisations for cast in-situ sheltered RC slab in Kunming, RCP 8.5 (Peng & Stewart, 2014b).

- Adaptation Strategies
  - C1 – increase cover by 5 mm
  - C2 - increase cover by 10 mm
  - S1 – increase concrete strength from 32 MPa to 40 MPa
  - S2 – increase concrete strength from 32 MPa to 50 MPa

Table 5: Costs of four adaptation strategies and damage for RC structural elements in Australia.

Costs	Structural element	*D* (mm)	C1: + 5 mm	C2: + 10 mm	S1: + 1 grade	S2: + 2 grades
C_{adapt} (\$/m^2)	Slabs – small	100	8.7	17.3	0.5	1.1
	Slabs – large	250	5.2	10.3	1.3	2.8
	Beams	500	7.9	15.9	2.5	5.5
C_{damage} (\$/m^2)	1000					
C_{adapt} / C_{damage}	Slabs – small	100	0.0087	0.0173	0.0005	0.0011
	Slabs – large	250	0.0052	0.0103	0.0013	0.0028
	Beams	500	0.0079	0.0159	0.0025	0.0055

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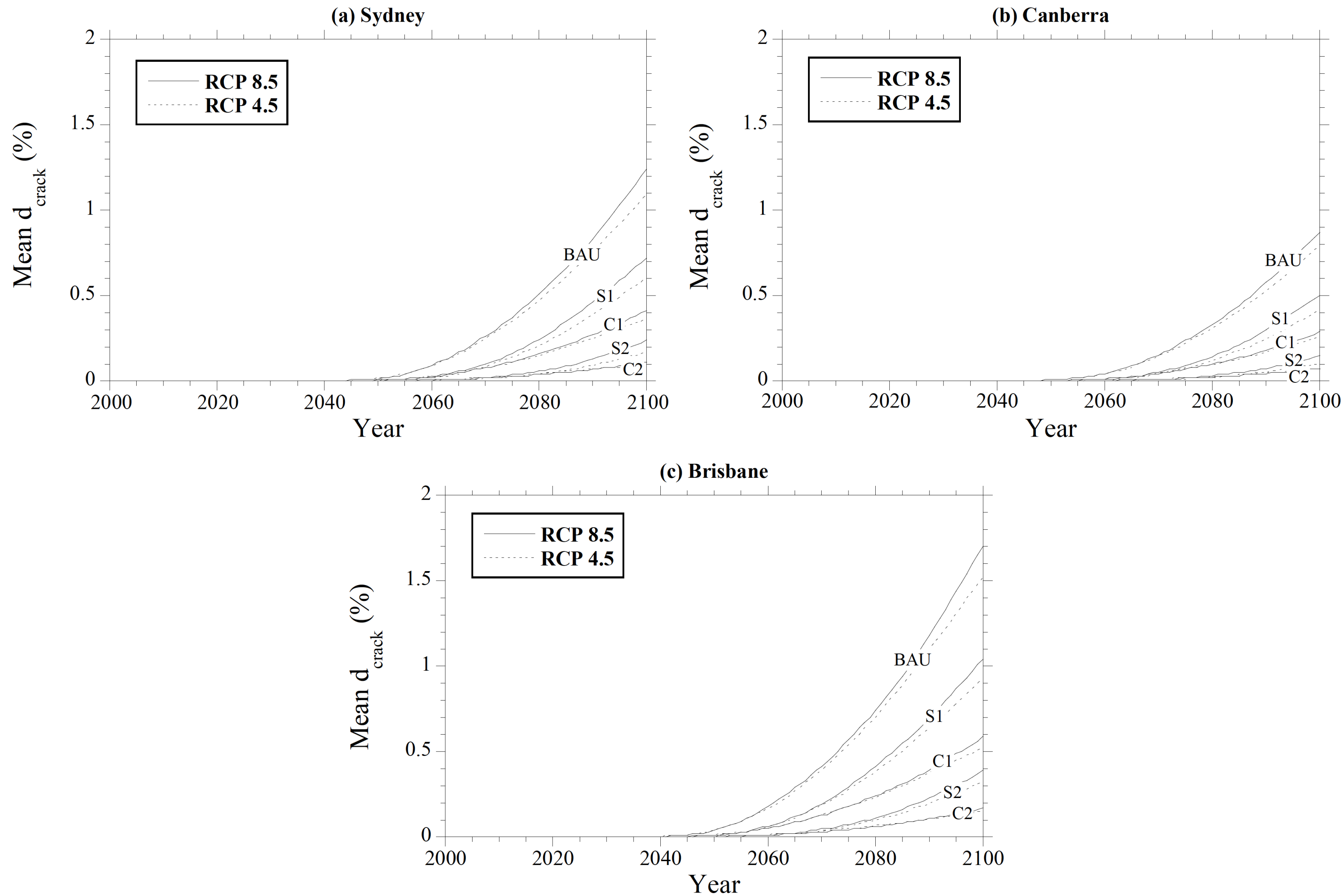

Figure 5: Mean extent of surface corrosion damage of BAU and four adaptation strategies for RC buildings in Sydney, Canberra and Brisbane under RCP 8.5 and RCP 4.5 emission scenarios.

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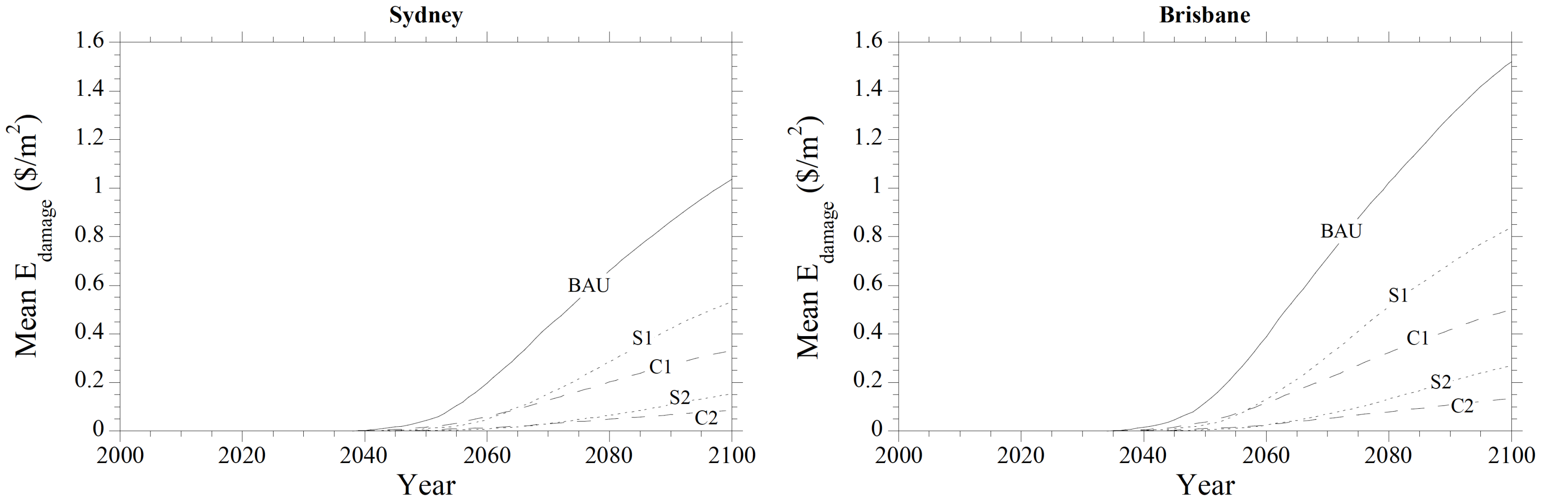

Figure 6: Expected damage costs ($/m^2) of BAU and four adaptation strategies for RC buildings in Sydney and Brisbane under RCP 8.5 emission scenario.

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Table 6: Mean NPV of four adaptation strategies for RC slabs and beams in three cities.

		slab 100 mm			slab 250 mm			beam		
		RCP 8.5	RCP 4.5	Year 2015	RCP 8.5	RCP 4.5	Year 2015	RCP 8.5	RCP 4.5	Year 2015
Sydney	C1	-8.0	-8.1	-8.2	-4.5	-4.6	-4.7	-7.2	-7.3	-7.4
	C2	-16.3	-16.4	-16.6	-9.3	-9.4	-9.6	-14.9	-15.0	-15.2
	S1	0.0	0.0	-0.1	-0.8	-0.8	-0.9	-2.0	-2.0	-2.1
	S2	-0.2	-0.3	-0.4	-1.9	-2.0	-2.1	-4.6	-4.7	-4.8
Canberra	C1	-8.2	-8.3	-8.4	-4.7	-4.8	-4.9	-7.4	-7.5	-7.6
	C2	-16.7	-16.7	-16.8	-9.7	-9.7	-9.8	-15.3	-15.3	-15.4
	S1	-0.2	-0.2	-0.2	-1.0	-1.0	-1.0	-2.2	-2.2	-2.2
	S2	-0.5	-0.5	-0.6	-2.2	-2.2	-2.3	-4.9	-4.9	-5.0
Brisbane	C1	-7.7	-7.8	-7.9	-4.2	-4.3	-4.4	-6.9	-7.0	-7.1
	C2	-15.9	-16.0	-16.3	-8.9	-9.0	-9.3	-14.5	-14.6	-14.9
	S1	0.2	0.1	0.1	-0.6	-0.7	-0.7	-1.8	-1.9	-1.9
	S2	0.1	0.1	-0.1	-1.6	-1.6	-1.8	-4.3	-4.3	-4.5

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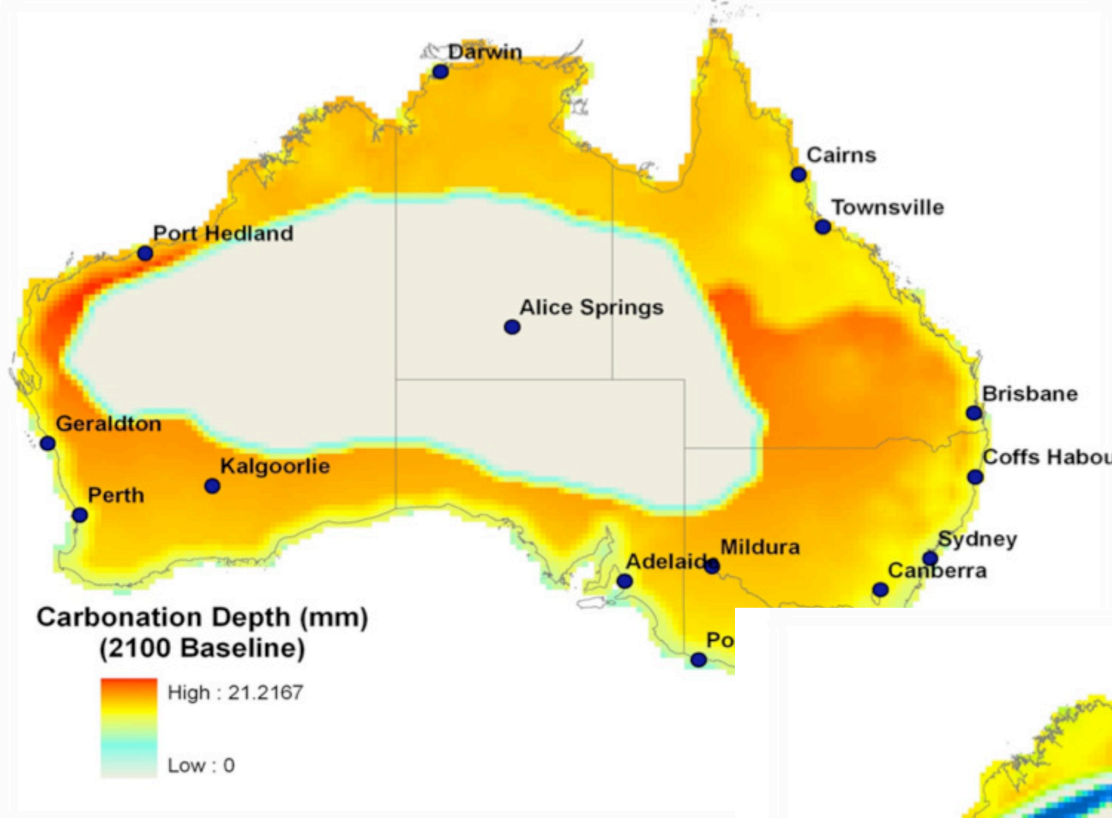
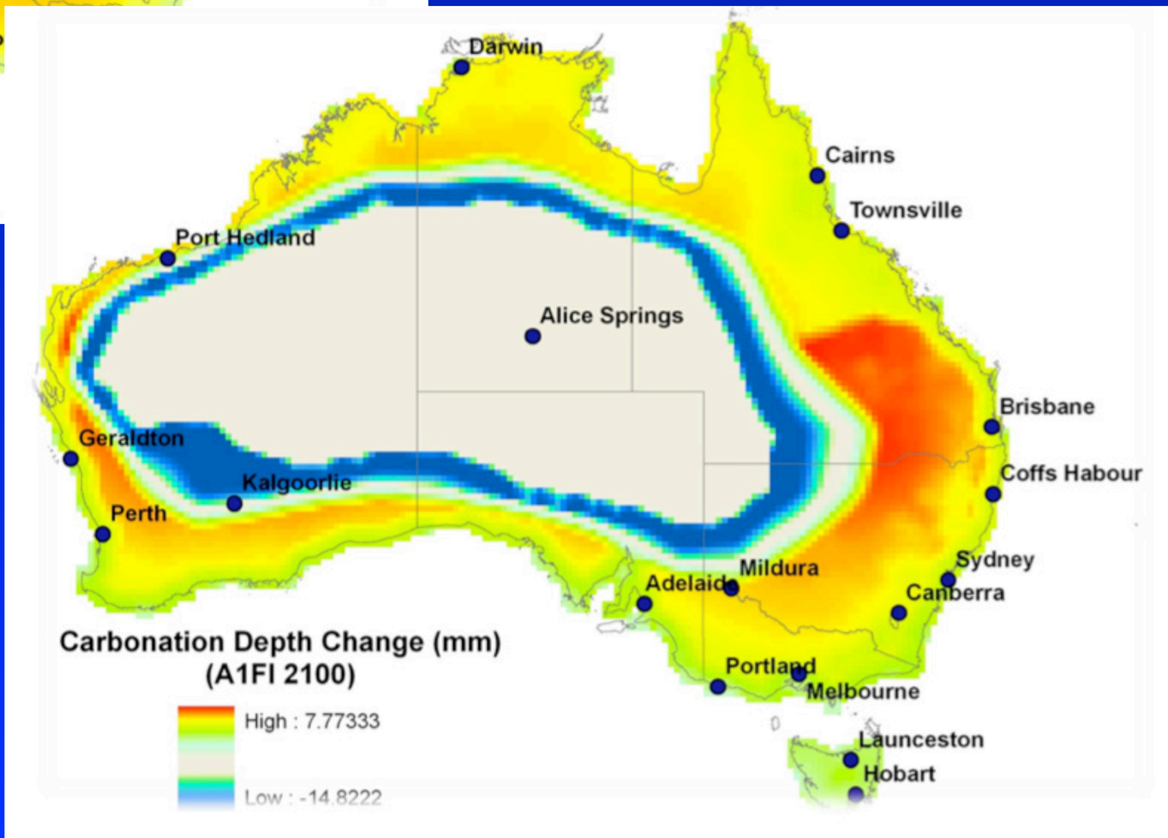
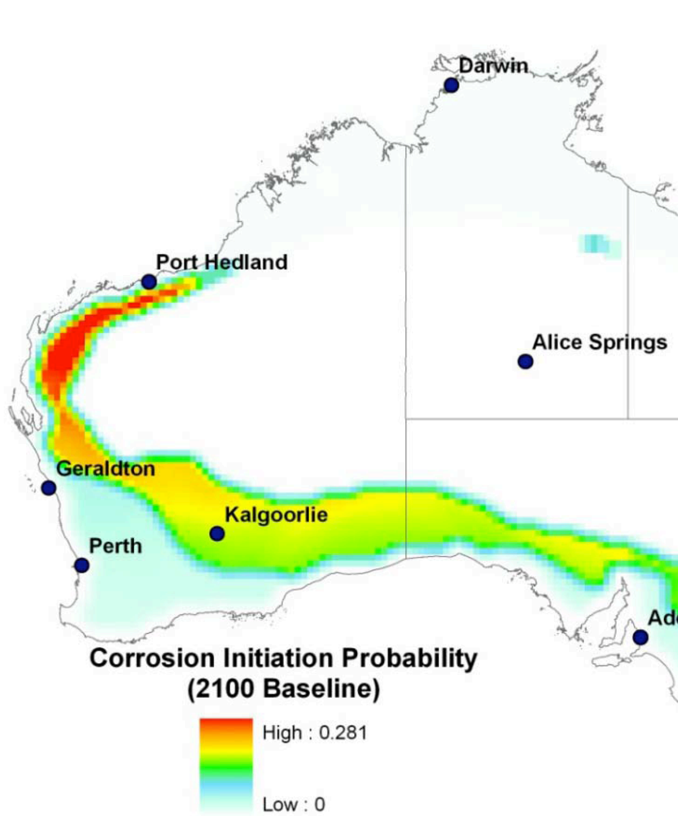


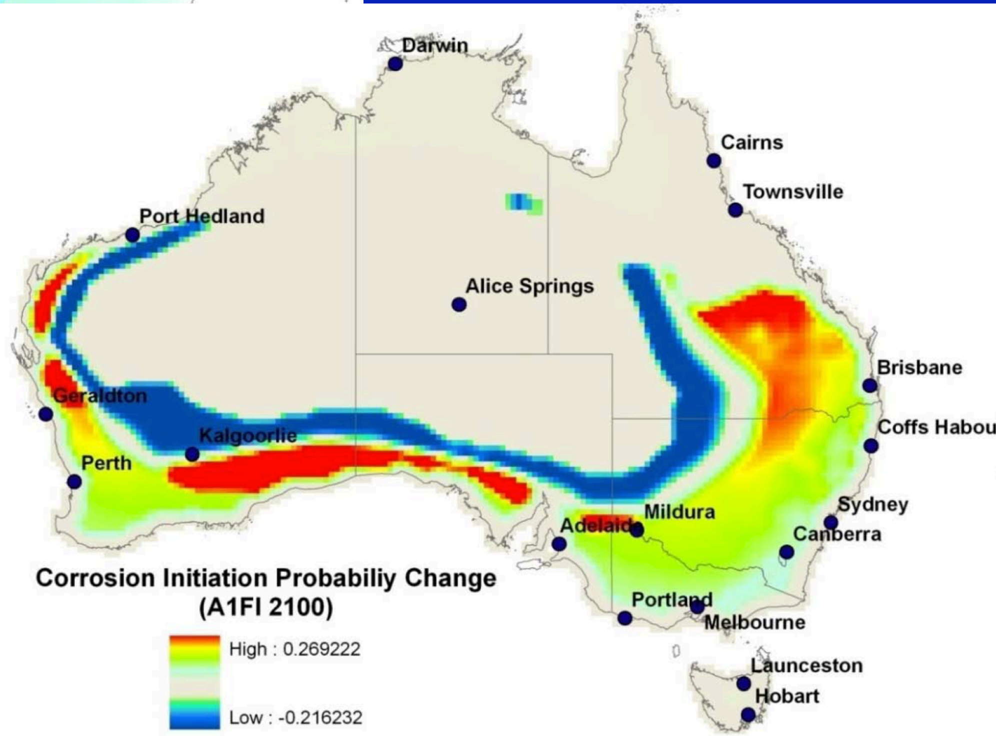
Carbonation **Depth**



Carbonation

Probability of Corrosion Initiation





(b) Change in corrosion initiation probability due to climate change

Figure 5-4. Projections of carbonation-induced corrosion initiation probability and its change due to climate change by 2100

Thank you!

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