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A Probabilistic Cumulative Damage Model for Service Life Prediction of Concrete Structures

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Introduction

- Concrete structures: multiple components
  - aging and requiring maintenance (e.g. bridges)
  - reduced strength, serviceability, functionality
  - several failure mechanisms with interaction- very complex to model

- Multiple deterioration mechanisms & failure modes
  - corrosion, freezing & thawing, alkali-aggregate reaction
  - fatigue, overstress (overload and/or under-strength)
  - partial/total collapse (bending, shear, punching shear,..)
  - loss of serviceability (excessive deformation, cracking)

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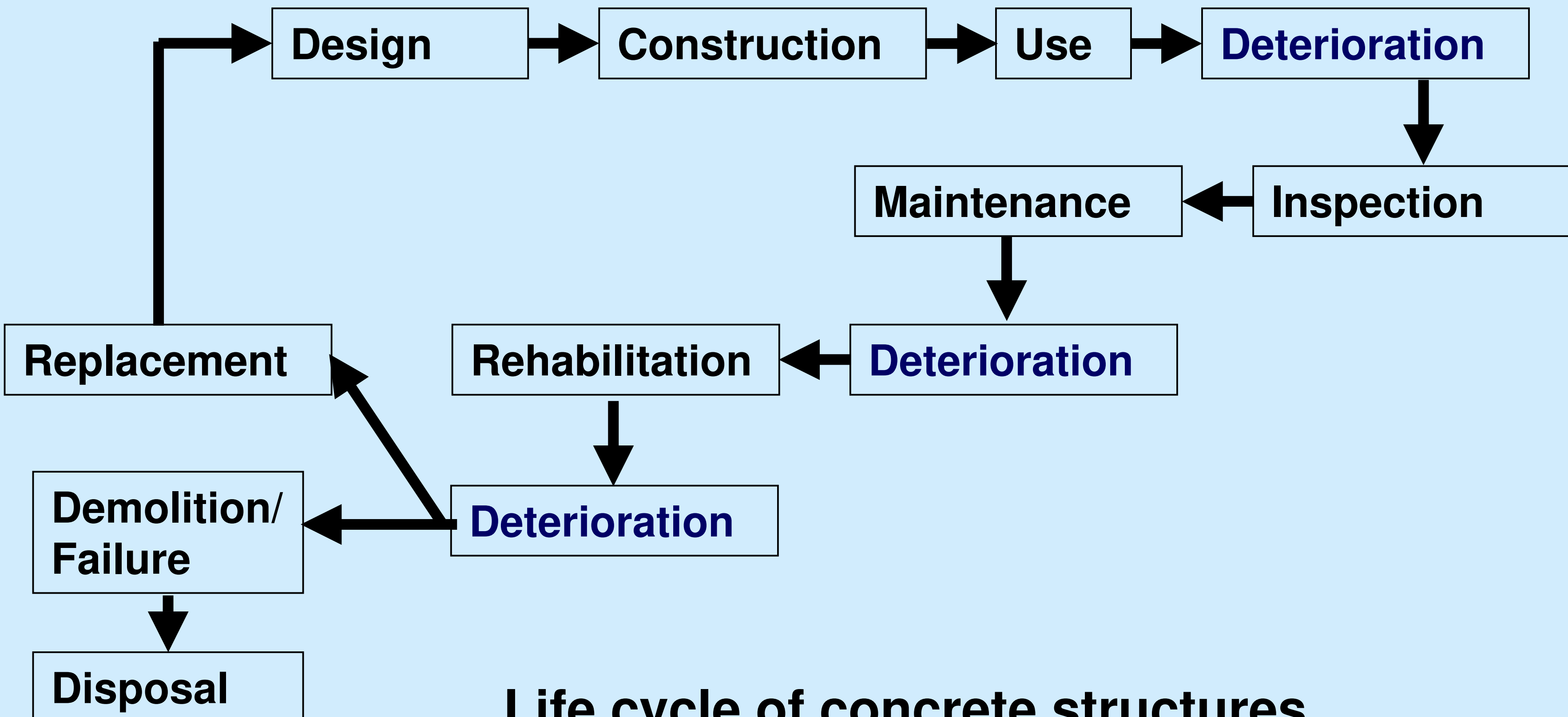
Introduction

- Causes of deterioration/failure
  - Increased loads
  - Aggressive environment
  - Reduced strength and/or stiffness
  - Inadequate design, construction, and maintenance

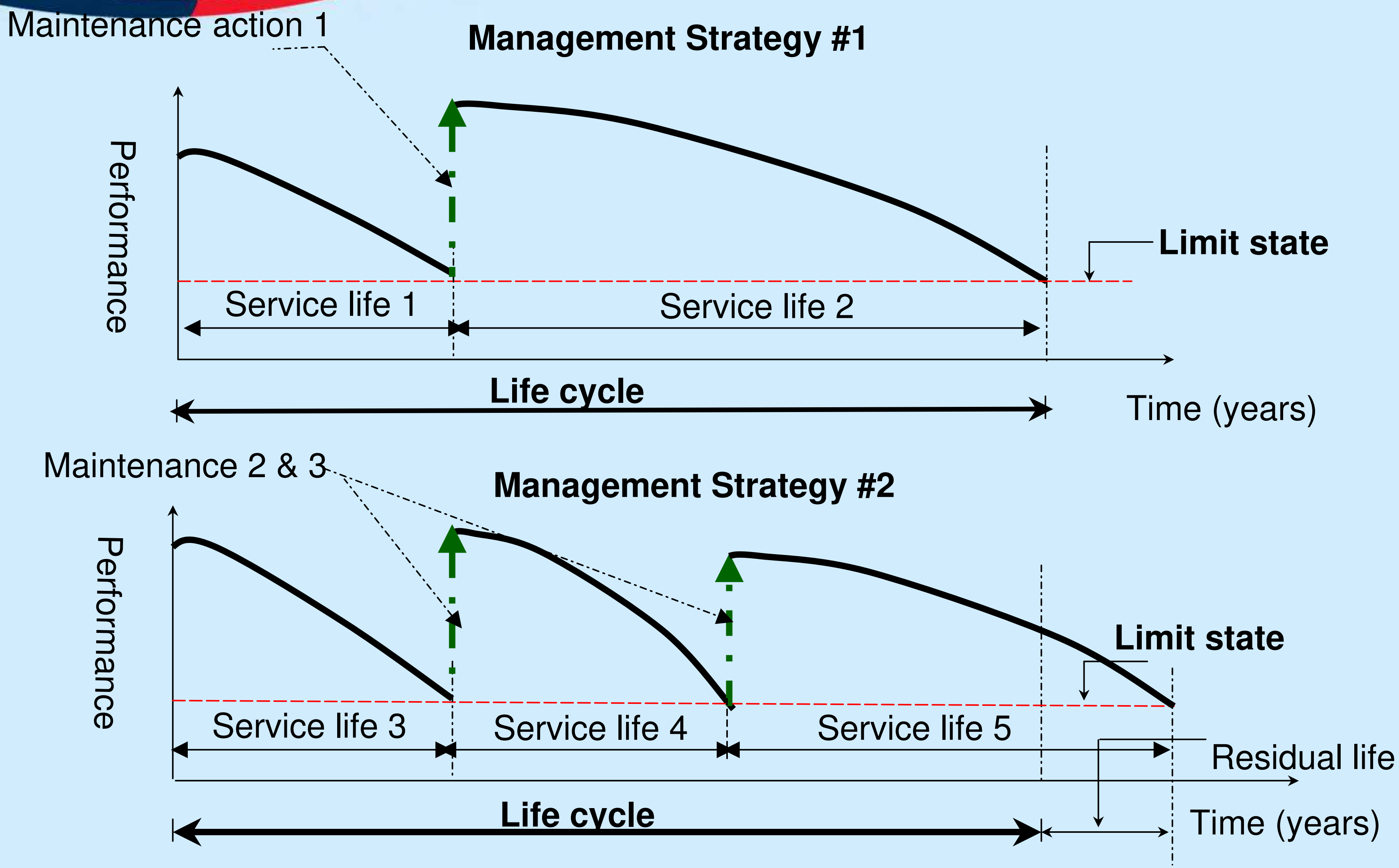
- Consequences of deterioration/failure
  - reduced safety, serviceability and service life
  - reduced level of service or functionality
  - increased risk of fatalities/injuries
  - increased maintenance and user costs
  - increased environmental impact

Performance of Concrete Structures



Life cycle of concrete structures

Performance of Concrete Structures



Performance of Concrete Structures

- Need service life models to:
  - Predict times it take to reach relevant limit states for different design and maintenance options
  - Ensure safety, serviceability & functionality
  - Evaluate life cycle costs
  - Optimize design, inspection and maintenance

- Definitions:
  - Service life: time to reach a limit state: time to failure
  - Life cycle: time period for analysis
  - Residual life remaining life at end of life cycle

Performance of Concrete Structures

- Benefits of life cycle performance modeling
  - identify critical structures/components
  - determine optimal times for maintenance
  - identify optimal maintenance strategies
  - extend service life of structures
  - minimize life cycle costs
  - determine required funding over life cycle
  - optimize the design of new structures

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Performance of Concrete Structures

- Prediction of life cycle performance of concrete structures: complex problem
  - structures deteriorate at different rates
  - uncertainty in loading, material properties, deterioration mechanisms, structural response, etc.
  - lack of reliable performance data
  - many owners/engineers use qualitative indicators to assess structural performance

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Performance of Concrete Structures

- Existing service life models
  - empirical models (accelerated life aging)
  - heuristic models
  - factorial models
  - logistic models
  - mechanistic models
  - cumulative damage models
  - shock models
  - probabilistic models

Performance of Concrete Structures

- Existing probabilistic service life models
  - statistical lifetime models
  - first or second order reliability models
  - Monte-Carlo simulation-based models
  - outcrossing models
  - stochastic finite element models
  - **probabilistic cumulative damage models**

Probabilistic Cumulative Damage Models

- Progressive accumulation of irreversible damage
  - cracks, spalls, delamination due to corrosion
  - cracks due to load, imposed deformations, freeze-thaw cycles, alkali-aggregate reactivity
  - inelastic deformations, fatigue, etc.
- Consideration of uncertainty
- Compatible with existing inspection methodologies of different structural concrete systems

Probabilistic Cumulative Damage Models

- PCD model 1
  - deterministic law for damage accumulation
  - parameters as random variables or processes
  - time-dependent accumulated damage
- PCD model 2- Bogdanoff’s model
  - evolutionary probabilistic model from the start
  - probabilistic distribution of accumulated damage

Probabilistic Cumulative Damage Models

- Bogdanoff's PCD models
  - based on Markovian processes: simple and practical stochastic processes
  - require limited amount of data
  - models can be easily updated with new data
  - can model impact of maintenance

Probabilistic Cumulative Damage Models

- Probabilistic distribution of damage:
  - depends on “duty” or “stress” cycle
  - depends on damage accumulated at start of stress cycle
  - **does not depend** on how the damage was accumulated up to the start of stress cycle
  - damage accumulation: time-increasing and progressive (no “shock” type of damage)

Probabilistic Cumulative Damage Models

- Probabilistic distribution of damage
  - high noise-to-signal ratios: large fluctuations from mean response
  - uncertainty in initial condition
  - uncertainty in damage accumulation

➡ **Deterioration of concrete structures modeled as a stochastic process**

Probabilistic Cumulative Damage Models

- Probabilistic distribution of damage
  - damage discretized into set of states: 1,2,…,b
  - b= absorbing or "failure" state
  - future state is independent of past states given present state ("memoryless" process)

$$P(S_{t+1}=s_{t+1} \mid S_t=s_t, S_{t-1}=s_{t-1}, .., S_0=s_0)=P(S_{t+1}=s_{t+1} \mid S_t=s_t)$$

Probabilistic Cumulative Damage Models

- Probabilistic damage distribution defined by:
  - transition probability matrix for each stress cycle

  $\mathbf{P}=\{P_{jk}\}$: transition matrix   j=1,2,…n; k=1,2,…,n

  Pjk= probability of damage being in state k after a stress cycle given it was in state j at start of stress cycle

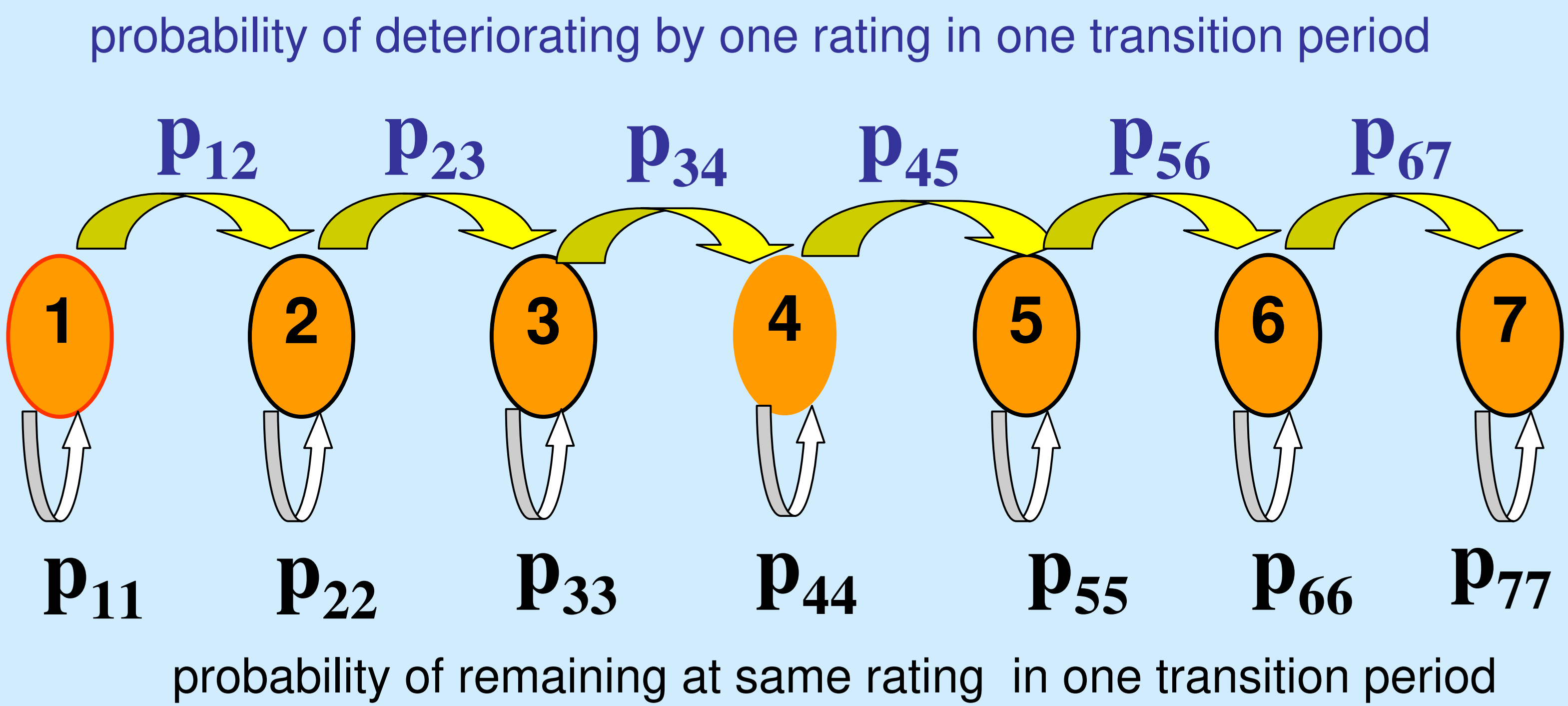
  - initial damage at t=0:

  $\mathbf{p}_0=[p_0(1)\ \ p_0(2) \ldots\ldots p_0(b)]$ =vector of initial state of damage

Probabilistic Cumulative Damage Models

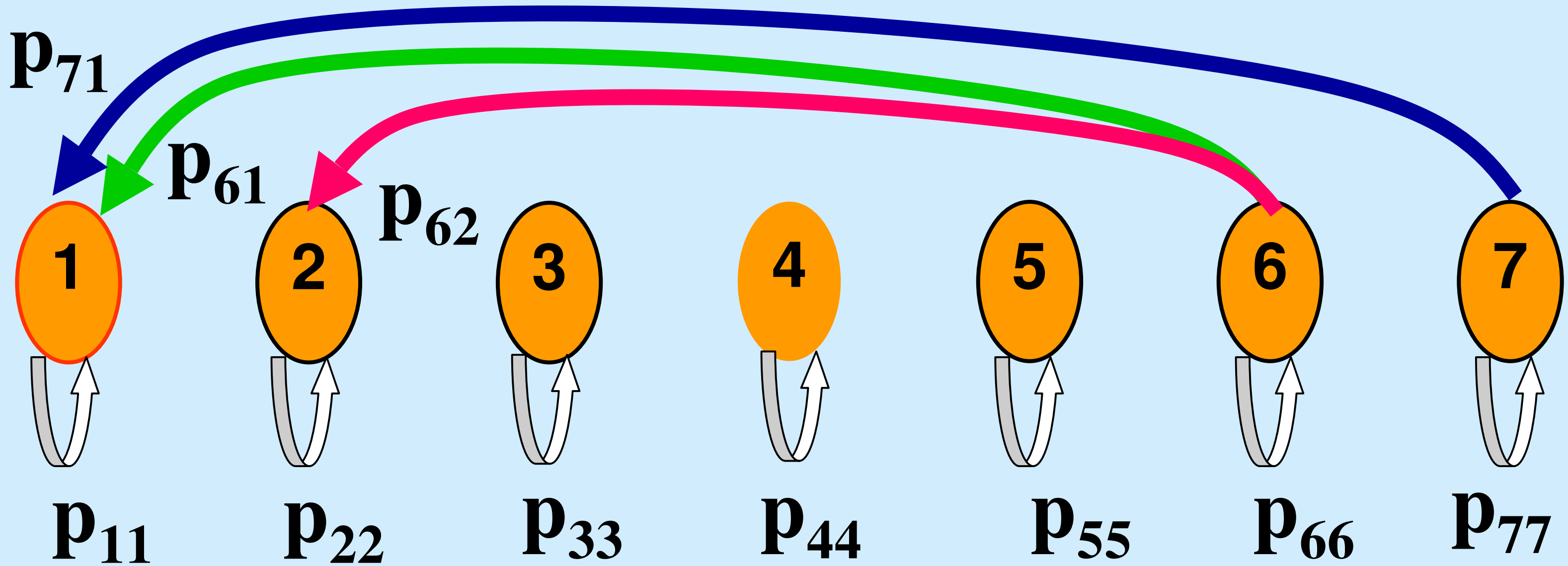
State of Structure	Description
1	Excellent Condition
2	Good Condition
3	Acceptable Condition
4	Fair Condition
5	Poor Condition
6	Urgent Condition
7	Critical Condition

Probabilistic Cumulative Damage Models



Unit-Jump Markov Chain Deterioration Model

Probabilistic Cumulative Damage Models



p_{nm}= probability of upgrading from state n to state m within one transition

Modeling Impact of Maintenance on Performance

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Probabilistic Cumulative Damage Models

- Prediction of time-dependent damage

$$\mathbf{p}_t = \mathbf{p}_0\, \mathbf{P}_1\, \mathbf{P}_2 \ldots\ldots \mathbf{P}_t$$

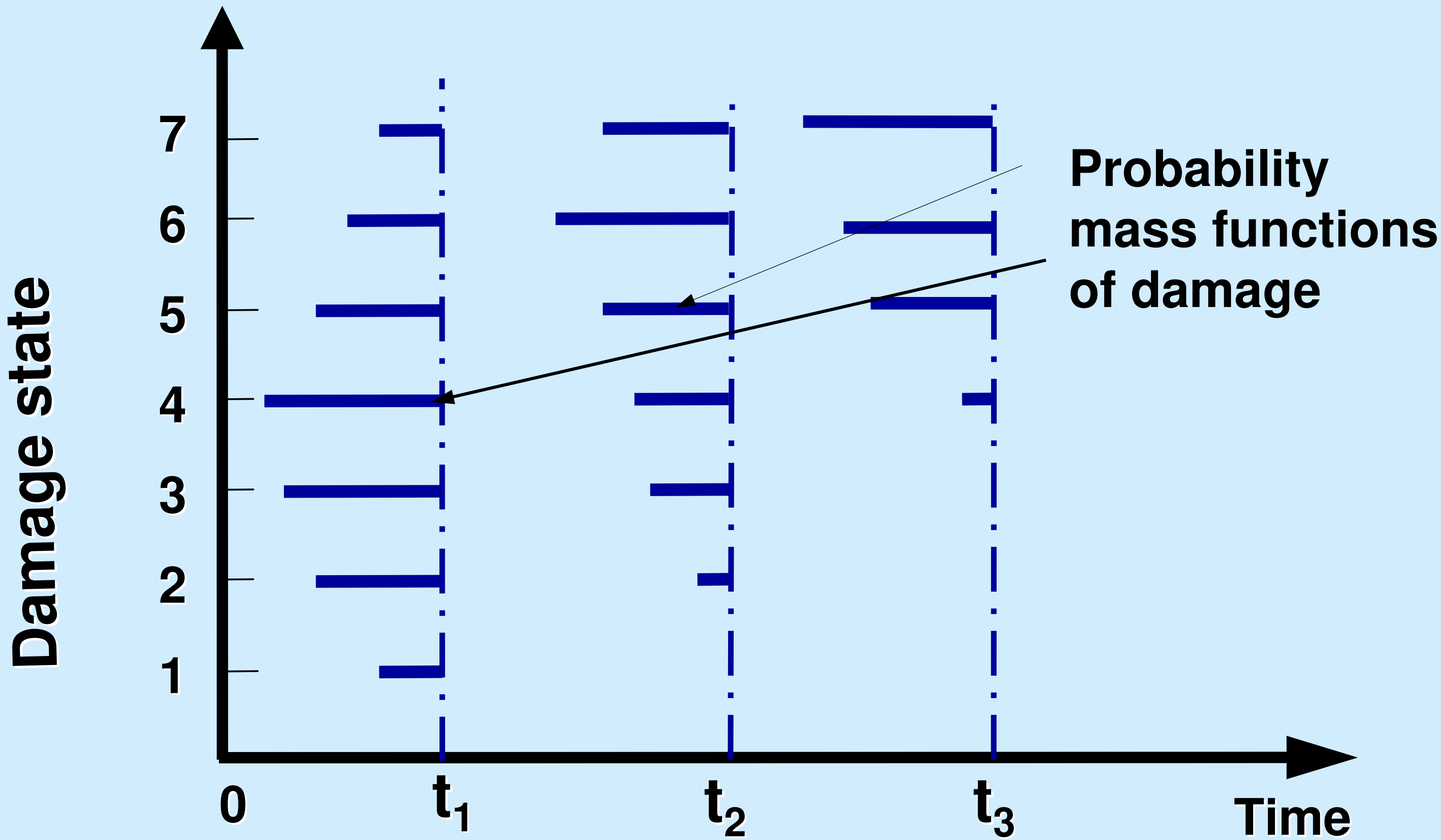
$\mathbf{p}_t$ = vector of state of damage at time t

$\mathbf{P}_j$= transition matrix for j^{th} stress cycle

- If stress cycles are constant over life of structure

$$\mathbf{p}_t = \mathbf{P}_0\, \mathbf{P}^t$$

Probabilistic Cumulative Damage Models



Probabilistic Cumulative Damage Models

- Cumulative distribution function of damage
  - D(t)= state of damage at time t

    $F_{Dt}(j) = P\,[D(t) \leq j] = \Sigma_k\, p_t\,(k) \quad k=1,\ldots, j$
  - Expected damage

    $E[D(t)] = \Sigma_k\, k\, p_t\,(k) \qquad k=1,\ldots\ldots, b$

- Service life:T=Time to absorption (i.e. reaching state b)

  cdf: $F_T(t) = P\,(T \leq t) = p_t(b) \qquad t=1,2,\ldots,n$

  mean T: $E(T) = \Sigma_t\,[1- F_T(t)\,]$

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Probabilistic Cumulative Damage Models

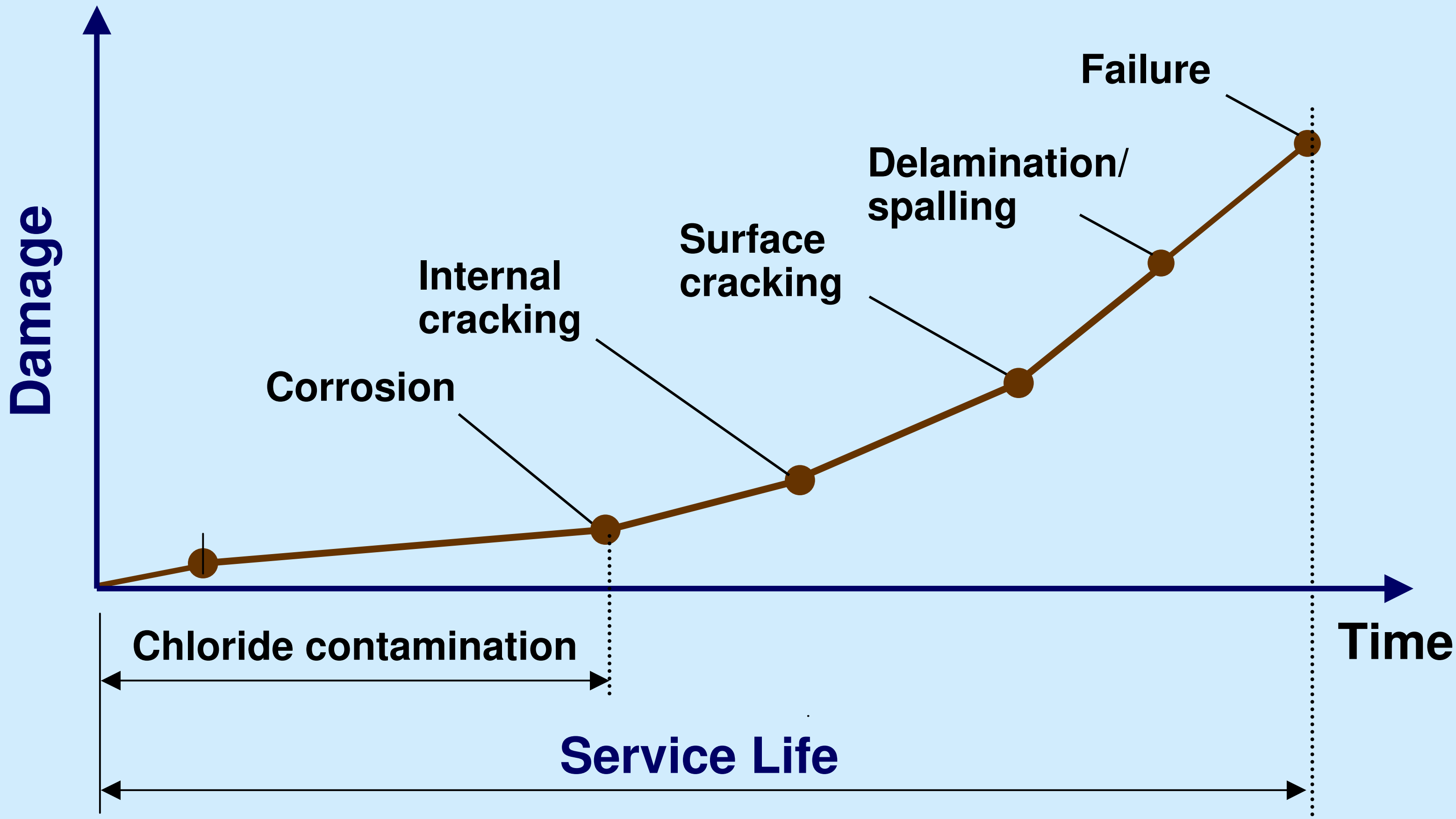
- Model development
  - Historical field performance data
  - Bayesian updating with additional data
- Explanatory variables
  - Age
  - Structural system type
  - Environment
  - Loading
  - Quality of design / protection/ construction
  - Maintenance option

Example: Concrete Bridge Decks

- Reinforced concrete bridge decks
  - Most deteriorated bridge elements
  - 1/3 to 1/2 projected bridge maintenance costs

- Development of PCD model for bridge decks
  - historical field performance data (min. 2 points in time)
  - explanatory variables
    - highway class
    - environmental exposure
    - average daily traffic
    - average daily truck traffic

Example: Concrete Bridge Decks



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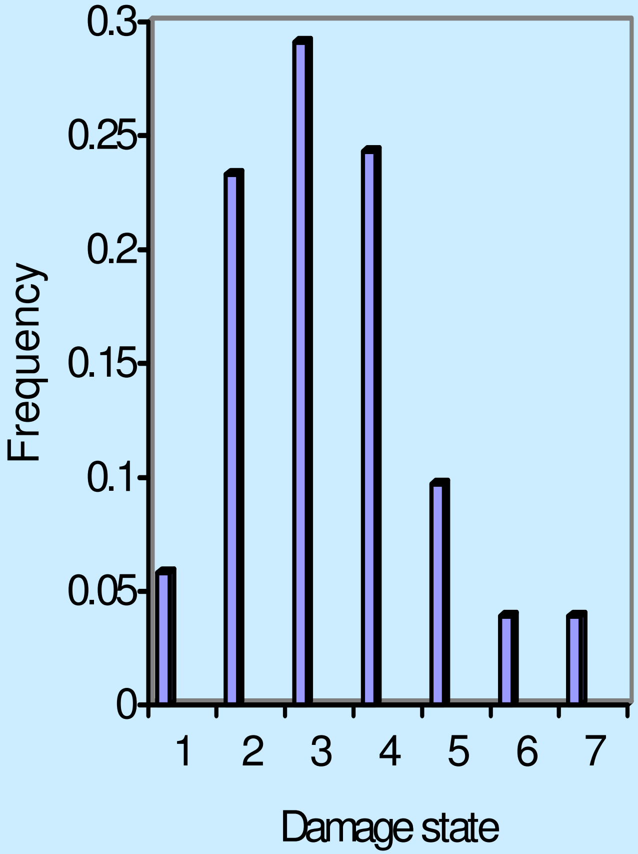
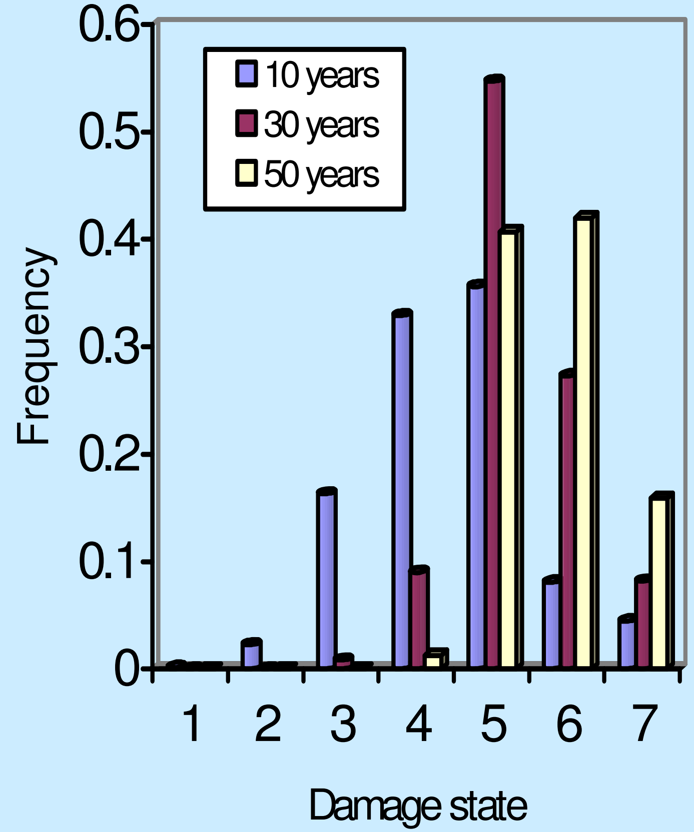
Example: Concrete Bridge Decks

$$
\mathbf{P} = \begin{bmatrix}
0.70 & 0.30 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.85 & 0.15 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.90 & 0.10 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.98 & 0.02 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.98 & 0.02 \\
0 & 0 & 0 & 0 & 0 & 0 & 1.00
\end{bmatrix}
$$

Example: Concrete Bridge Decks



Current condition



Conditions after 10, 30, 50 years

Expected damage
3.36 @ 0
5.33 @ 30 years

Conclusions

- Service life of concrete structures can be predicted using probabilistic cumulative damage (PCD) models
- PCD models capture time-dependence
and uncertainty of performance of concrete structures

- PCD models provide effective decision support for design and maintenance of concrete structures
- PCD models are practical and require limited data
- PCD models can also be used for a large group of structures

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