3rd Probabilistic Workshop
BOKU Wien
24 November 2005

Overview on the Asset Integrity Management of Large Structures

Daniel Straub, Vasiliki Malioka & Michael Havbro Faber

Swiss Federal Institute of Technology, ETH Zürich

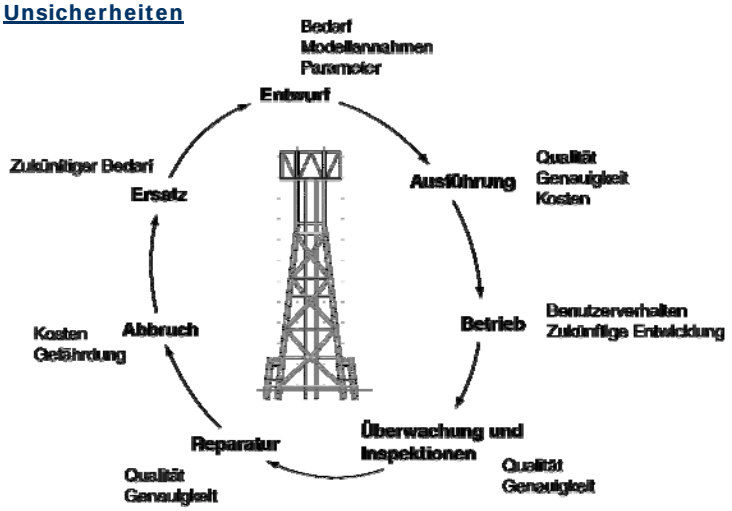
Outline

- Decision problems in large deteriorating structures
- Quantitative modelling of deterioration
  - in time
  - in space
- The effect of inspections
  - in time
  - in space
- Computational strategies (paper)
- Calculating of the expected cost of inspection and repair strategies
- Conclusions

Example results are included throughout the presentation
(Concrete structure subject to chloride-induced corrosion of the reinforcement)

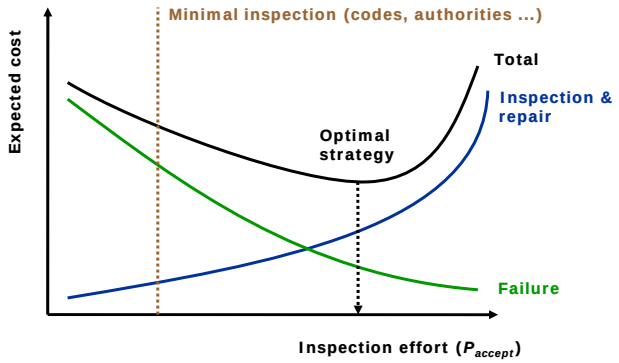
Life-cycle of a structure

Unsicherheiten



Decision problems in large deteriorating structures

- Decisions must be made under uncertainty
- For individual structural elements, such decisions can be optimized using Bayesian decision analysis



Decision problems in large deteriorating structures

ETH ibk

Decision problems in large deteriorating structures

ETH ibk

Decision problems in large deteriorating structures

- Decisions must be made under uncertainty
- For individual structural elements, such decisions can be optimized
- For large systems, many dependencies among individual elements/components must be considered:
  - Dependencies in the deterioration performance
  - Dependencies of the failure consequences
  - Dependencies of the inspection/repair costs
  - Inference from inspection of other parts of the system
- These dependencies must be taken into account when determining:
  - *What* to inspect for
  - *Where* to inspect
  - *When* to inspect
  - *How* to inspect

ETH ibk

Outline

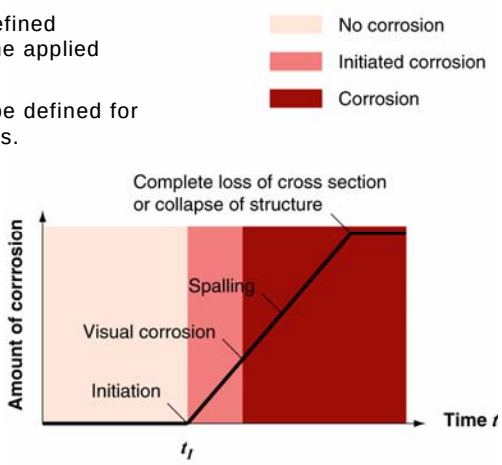
- Decision problems in large deteriorating structures
- **Quantitative modelling of deterioration**
  - **in time**
  - **in space**
- The effect of inspections
  - in time
  - in space
- Computational strategies (paper)
- Calculating of the expected cost of inspection and repair strategies
- Conclusions

ETH ibk

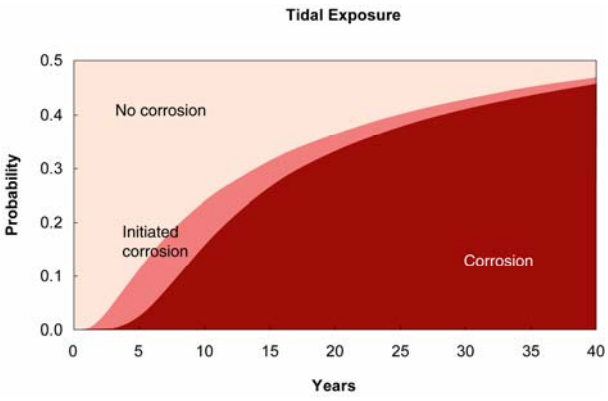
Quantitative temporal modelling of deterioration

- The state of the structure is expressed in terms of condition states, e.g., corrosion initiation and visible corrosion.
- Condition states must be defined quantitatively in terms of the applied corrosion models.

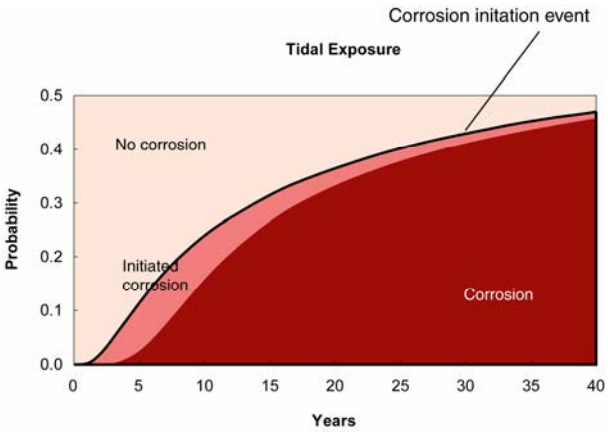
→ Limit state functions must be defined for the different condition states.



Quantitative temporal modelling of deterioration: Example



Quantitative temporal modelling of deterioration: Example

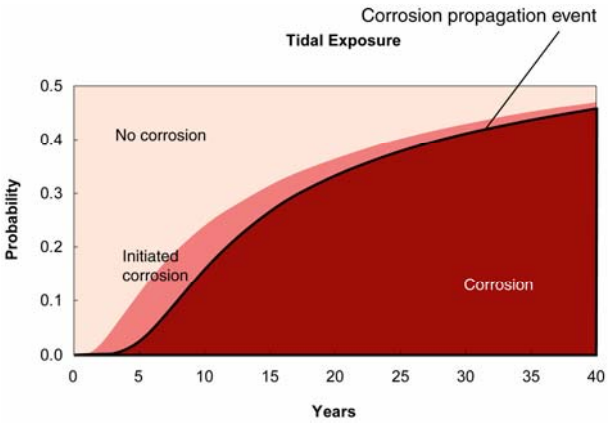


$$M_1 = g_1(t) = X_I T_I - t$$

$$T_I = \frac{d^2}{4D}\left(erf^{-1}\left(1-\frac{C_{CR}}{C_S}\right)\right)^{-2}$$

ETH ibk

Quantitative temporal modelling of deterioration: Example



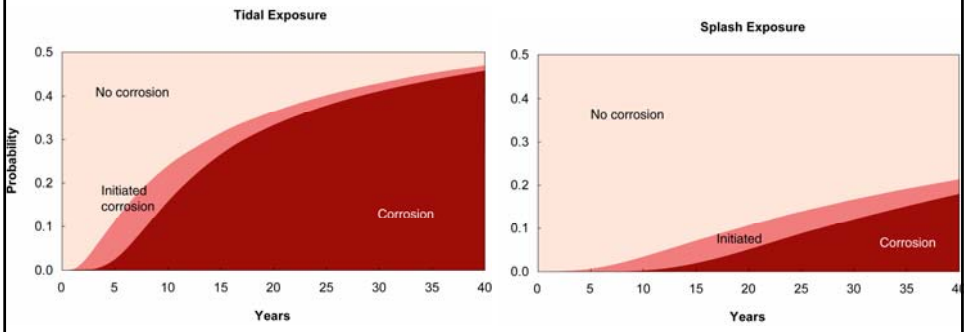
$$M_2 = g_2(t) = X_I T_I + T_P - t$$

$$T_I = \frac{d^2}{4D}\left(erf^{-1}\left(1-\frac{C_{CR}}{C_S}\right)\right)^{-2}$$

ETH ibk

Quantitative temporal modelling of deterioration: Example

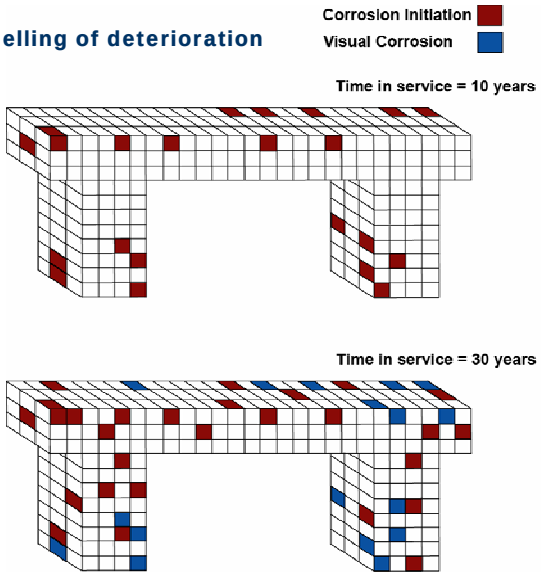
- Tidal vs. splash exposure:



- The differences are observed for the same structure in different exposure classes

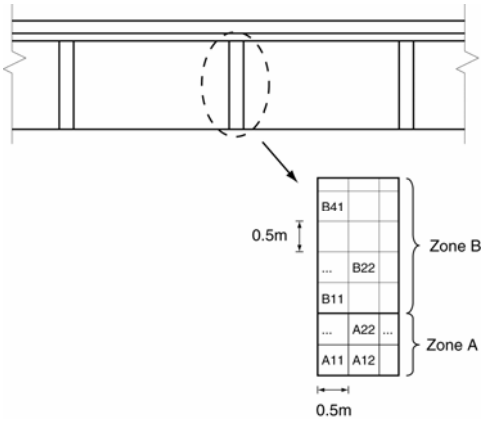
Quantitative spatial modelling of deterioration

- Deterioration varies over the structure
- Combined spatial and temporal modelling:



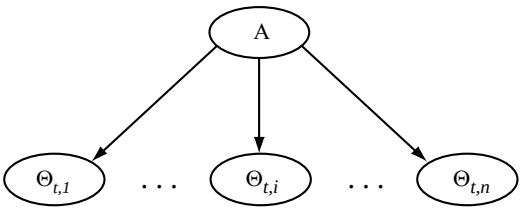
Quantitative spatial modelling of deterioration

- Spatial model is required
- Discretize into zones and elements
- Zones: Areas with the same parameters



Quantitative spatial modelling of deterioration

- Proposed spatial model:
- Discretize into zones and elements
- Zones: Areas with the same parameters
- Using hyper-parameters to represent the dependency among elements in one zone.

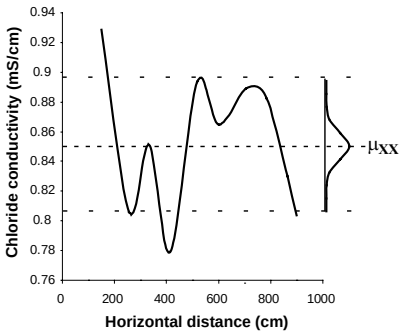


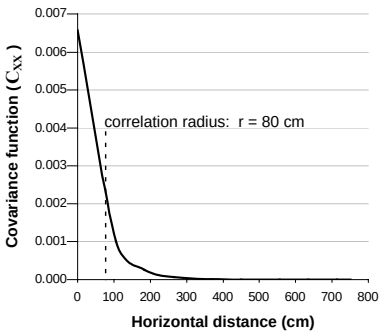
Hyper-parameters

Condition states at the *n* individual elements at different points in time *t*

Determine spatial variability through experiments

- Determine element size (elements are independent given the hyper-parameters)





$$f_{\mathbf{X}}(\mathbf{x}) = (2\pi)^{-m/2} \left|\mathbf{C}_{\mathbf{XX}}\right|^{-1/2} \exp\left[-\frac{1}{2}(\mathbf{x}-\mu_{\mathbf{XX}})^T \mathbf{C}_{\mathbf{XX}}^{-1}(\mathbf{x}-\mu_{\mathbf{XX}})\right]$$

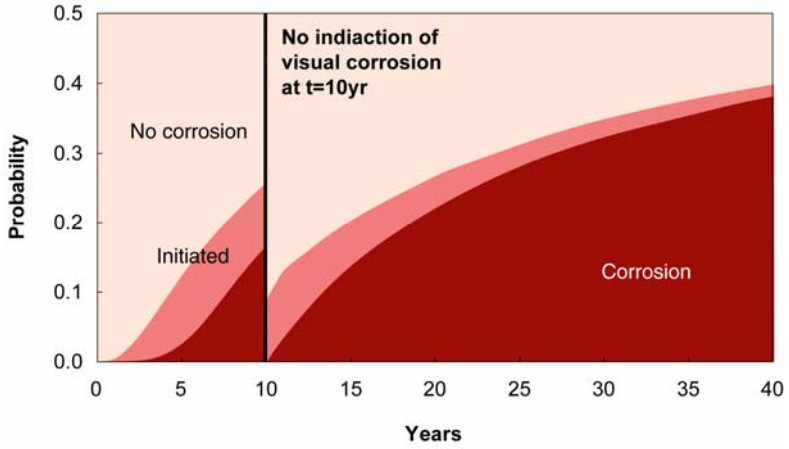
ETH ibk

Outline

- Decision problems in large deteriorating structures
- Quantitative modelling of deterioration
  - in time
  - in space
- **The effect of inspections**
  - **in time**
  - **in space**
- Computational strategies (paper)
- Calculating of the expected cost of inspection and repair strategies
- Conclusions

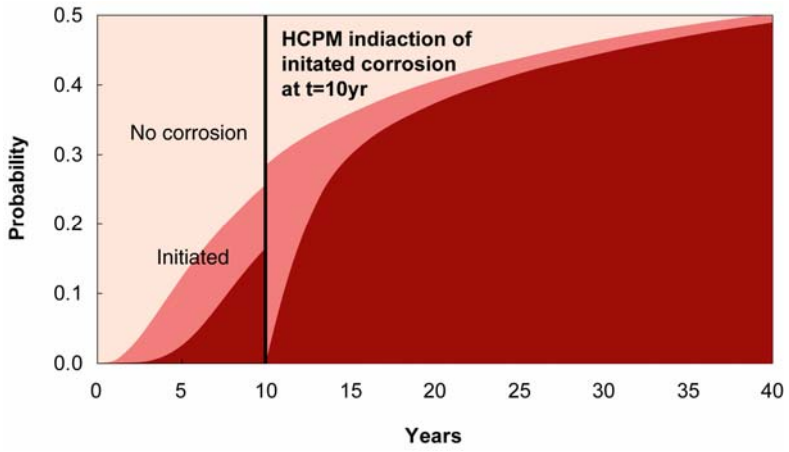
The effect of inspections in time

- Probabilistic deterioration models can be updated using Bayes' rule



The effect of inspections in time

- Probabilistic deterioration models can be updated using Bayes' rule



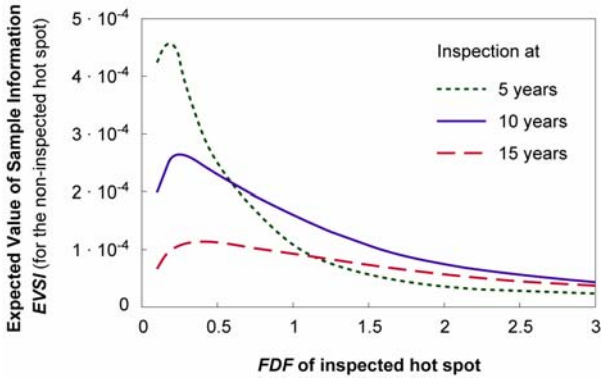
The effect of inspections in space

- Inspections provide information on the state of the element, but also of the entire system
- The effect on the system is a function of the dependencies in the model:
  - Full dependency: Inspection of 1 element is sufficient
  - No dependency: All elements must be inspected
- The value of an inspection of an element with regard to the other elements can be assessed

  (Straub & Faber, Structural Safety 2005)

The effect of inspections in space

- The value of inspecting an element with regard to another element (or the system):



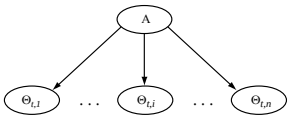
(Straub & Faber, Structural Safety 2005)

Outline

- Decision problems in large deteriorating structures
- Quantitative modelling of deterioration
  - in time
  - in space
- The effect of inspections
  - in time
  - in space
- **Computational strategies (paper)**
- Calculating of the expected cost of inspection and repair strategies
- Conclusions

Computational framework (paper)

- The computational framework facilitates the efficient updating with inspection results, accounting for both the spatial and temporal variability.
- The framework is based on the pre-calculation of the updated probabilities for given hyper-parameters **A**
- Using SRA/MCS, establish a database with:
- The probabilities for any structure are then calculated by an expectation operation over **A**



$$p_{\Theta_{t,i}}\left(\theta_i \middle| \boldsymbol{\alpha}\right)$$

$$p_{\Theta_{t,i}}\left(\theta_i \middle| z_i, \boldsymbol{\alpha}\right)$$

$$p_{\mathbf{A}}\left(\boldsymbol{\alpha}\right)$$

- With the algorithms provided in the paper, all type of information (in time and space) can be used to update both the temporal and spatial distribution in a highly efficient manner

Computational framework (paper)

- Example:

Resulting in no-indication
Resulting in indication

Time of HCPM

	25	25	25						
	25	25	25						
	25	25	25						
						35	35	35	
						35	35	35	
						35	35	35	

Probability of visible corrosion at t = 50yr

0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.48	0.27	0.27	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.48	0.48	0.27	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.27	0.27	0.27	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.57	0.17	0.17	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.17	0.17	0.57	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.17	0.17	0.17	0.35
0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

Computational framework (paper)

- Example:

Resulting in no-indication
Resulting in indication

Time of visual insp.

40	40	40	40	40	40	40	40	40	40
40	40	40	40	40	40	40	40	40	40
40	40	40	40	40	40	40	40	40	40
40	40	40	40	40	40	40	40	40	40
40	40	40	40	40	40	40	40	40	40

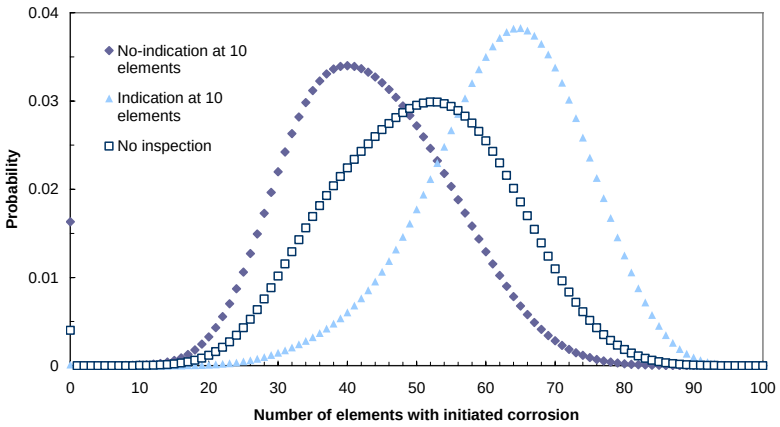
Probability of visible corrosion at t = 50yr

0.13	0.13	0.13	0.13	0.13	0.13	1	0.13	0.13	0.13
0.13	1	0.13	1	0.13	0.13	0.13	0.13	0.13	0.13
0.13	0.12	1	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.13	1	1	0.13	0.13	0.13	0.13	0.13	0.13	0.13
0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
0.27	0.27	0.27	0.27	0.27	0.27	0.48	0.13	0.13	0.27
0.27	0.27	0.27	0.27	0.27	0.27	0.13	0.13	0.48	0.27
0.27	0.27	0.27	0.27	0.27	0.27	0.13	0.13	0.13	0.27
0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

ETH ibk

Computational framework (paper)

- Example (HCPM at year 25)



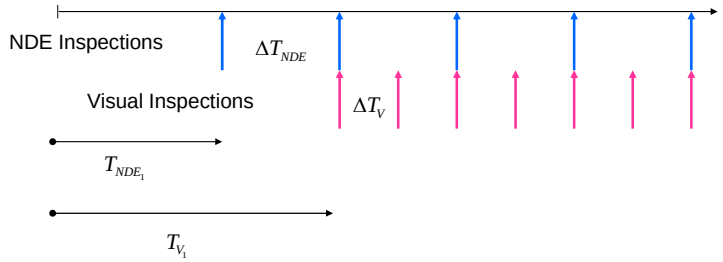
ETH ibk

Outline

- Decision problems in large deteriorating structures
- Quantitative modelling of deterioration
  - in time
  - in space
- The effect of inspections
  - in time
  - in space
- Computational strategies (paper)
- **Calculating of the expected cost of inspection and repair strategies**
- Conclusions

Define inspection strategies

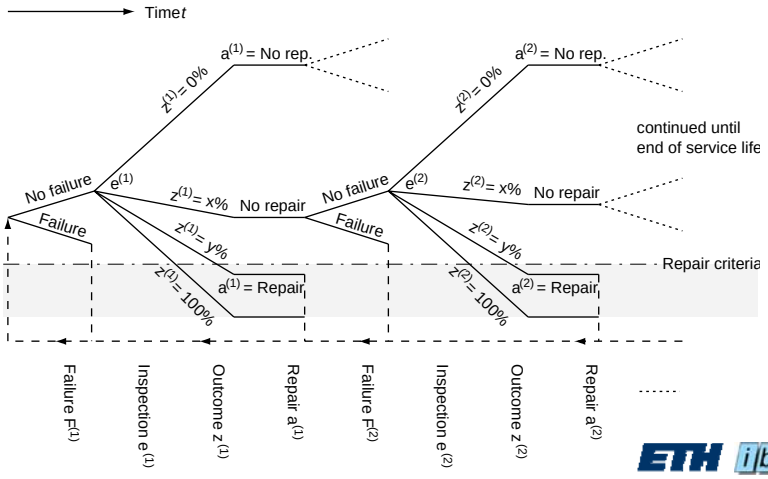
- *What percentage* of the structure should be inspected *when* and with *which method*?
- Define inspection/repair strategies:



- When should repair actions be carried out? Repair criteria should be given as a function of the inspection outcomes

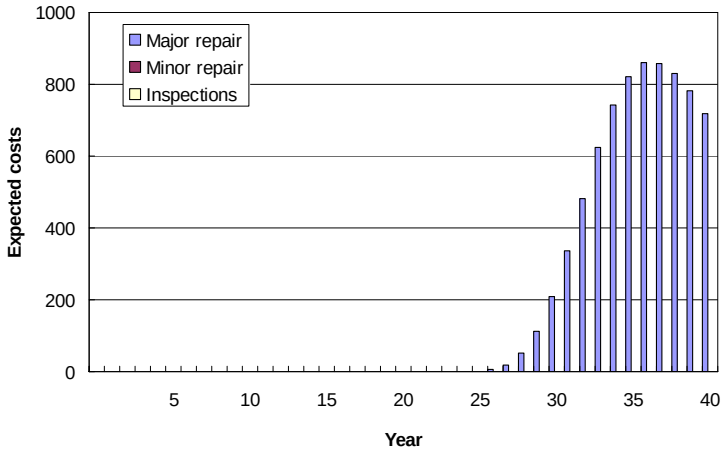
Calculating the inspected costs

- Decision tree (with much additional complexity compared to the case for the single element)



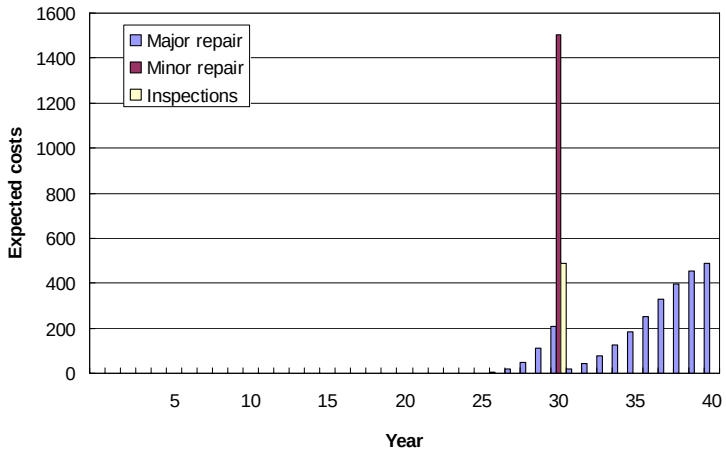
Optimizing inspection strategies

- Example (Zone with 100 elements) – Expected cost without inspections:



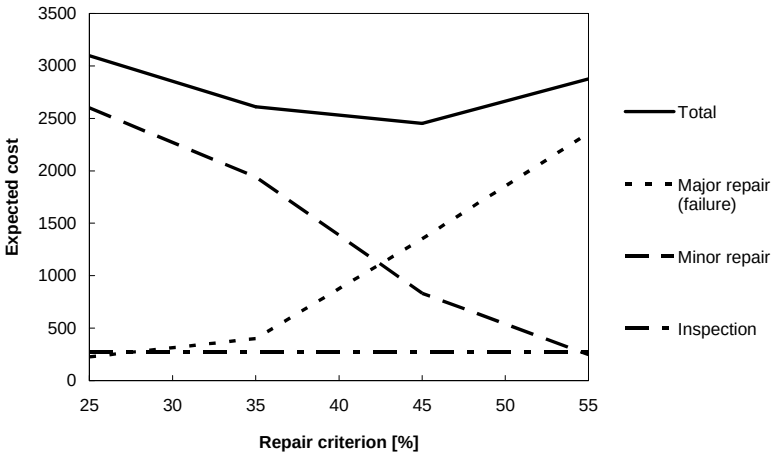
Optimizing inspection strategies

- Example – Expected cost with 50% HCPM inspection at year 30:



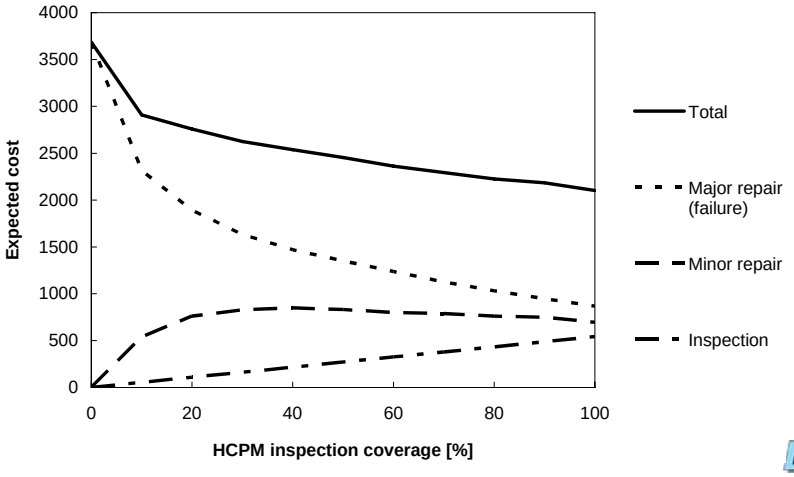
Optimizing inspection strategies

- Optimize repair criterion for HCPM outcome:



Optimizing inspection strategies

- Optimize inspection coverage for HCPM outcome:



Conclusions

- Asset integrity management for large deteriorating structures requires that both the temporal & spatial variability is explicitly addressed by the model
- The presented framework allows for explicit consideration of inspection results at different times and locations
  - → An updated probabilistic model is available at all points in time for the planning of future actions
- Due to the computational efficiency, the model allows for an optimization of inspection efforts and repair strategies
- Thank you for your attention