55th Brazilian Congress on Concrete
3rd Symposium on Subway, Railway and Highway Infrastructure
Gramado, Rio Grande do Sul, Brazil
November 1st, 2013

POLITECNICO DI MILANO

Life-Cycle Reliability Assessment of Concrete Bridges Exposed to Corrosion

Fabio Biondini

Department of Civil and Environmental Engineering, Politecnico di Milano

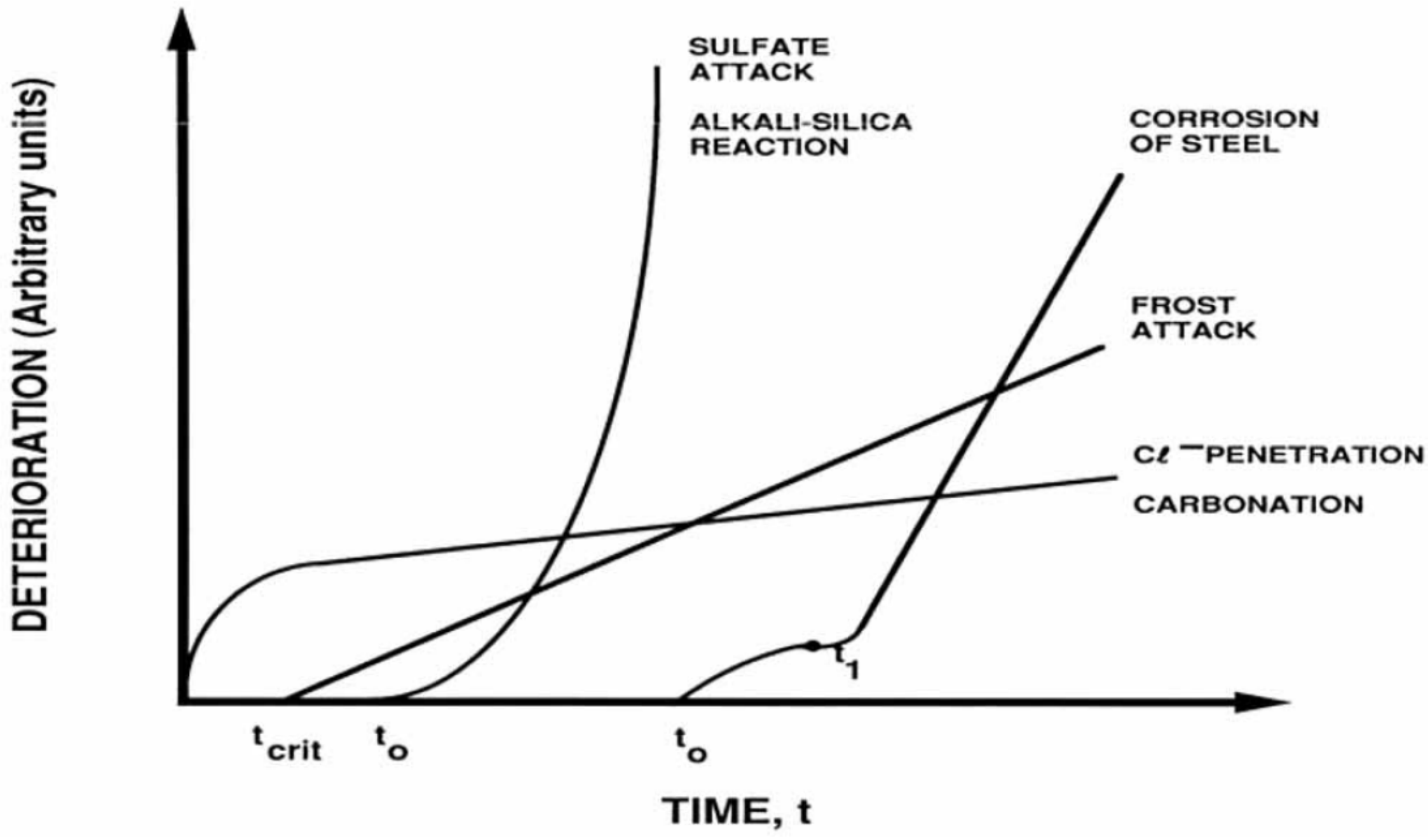
Aging and Deterioration of Bridges

- The **life-cycle performance of bridge and infrastructure systems** is affected by time-variant deterioration effects of aging and damage processes of materials and components.

- Deterioration mechanisms are generally complex and their effects over time depend on both the **damage process** and **type of materials and structures**.

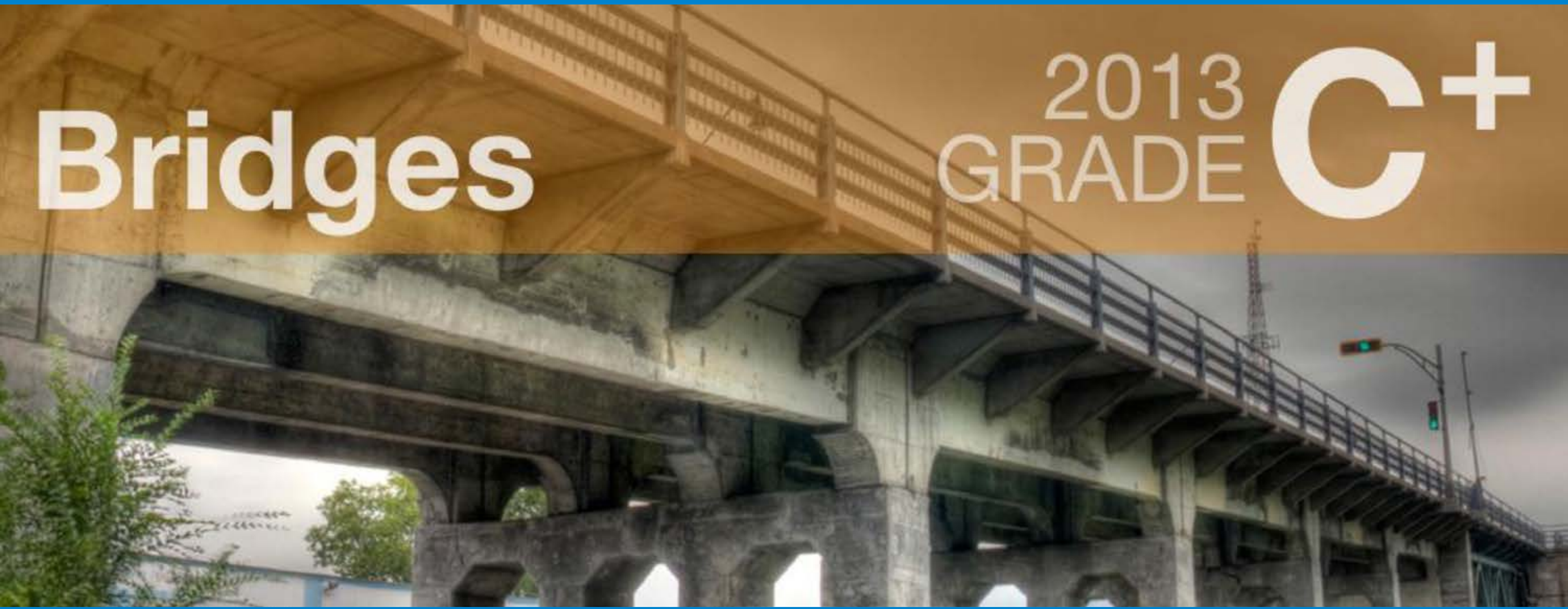
- For concrete bridges the **main sources of damage** include **chemical processes** associated to sulfate and chloride attacks and alkali-silica reactions, **physical processes** due to freeze/thaw cycles and thermal cycles, and **mechanical processes** such as cracking, abrasion, erosion, and fatigue.

Deterioration Processes



(Clifton and Knab 1989)

2013 REPORT CARD FOR AMERICA'S INFRASTRUCTURE ASCE



"In total, **one in nine of the nation's bridges** are rated as **structurally deficient**, while the **average age** of the nation's 607,380 bridges is currently **42 years**."

WWW.INFRASTRUCTUREREPORTCARD.ORG

Italian Networks:

- Railways 16,000 km
- Highways 3,400 km
- Roads 26,700 km

Life-Cycle Probabilistic Approach

- The condition rating of stocks of existing bridges and infrastructure networks indicates that the **economic impact of deterioration** is exceptionally high and emphasizes the importance of proper **maintenance and repair of structurally deficient bridges**.

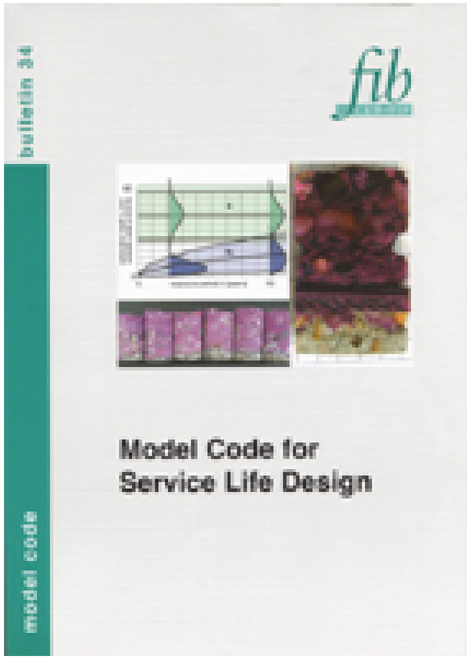
- These problems present a **major challenge to bridge engineering**, since the classical time-invariant structural design criteria and methods need to be revised to account for a proper modeling of the structural system over its **entire life-cycle** by taking the effects of deterioration processes, time-variant loadings, maintenance actions and repair interventions into account.

- In addition, because of the **uncertainty** in material and geometrical properties, in the physical models of deterioration processes, and in the mechanical and environmental stressors, a measure of the time-variant performance is realistically possible only in **probabilistic terms**.

Current State of Practice

- In recent years, **relevant advances** have been accomplished in the fields of modeling, analysis, design, maintenance, monitoring, and management of deteriorating bridges.
- Despite this research trend, **life-cycle concepts are not yet explicitly addressed** in design codes and the checking of system performance requirements is referred to the initial time of construction when the system is intact.
- In this approach, **design for durability** of concrete structures with respect to chemical-physical damage phenomena is based on simplified criteria associated with **classes of environmental conditions**.
- Such criteria introduce **threshold values** for concrete cover, water-cement ratio, amount and type of cement, among others, **to limit the effects of local damage** due to carbonation of concrete and corrosion of reinforcement.

Model Code for Service Life Design



Model Code for Service Life Design
fib Bulletin No. 34, 2006, pp. 116

1. General
2. Basis of design
3. Verification of Service Life Design
4. Execution and its quality management
5. Maintenance and condition control

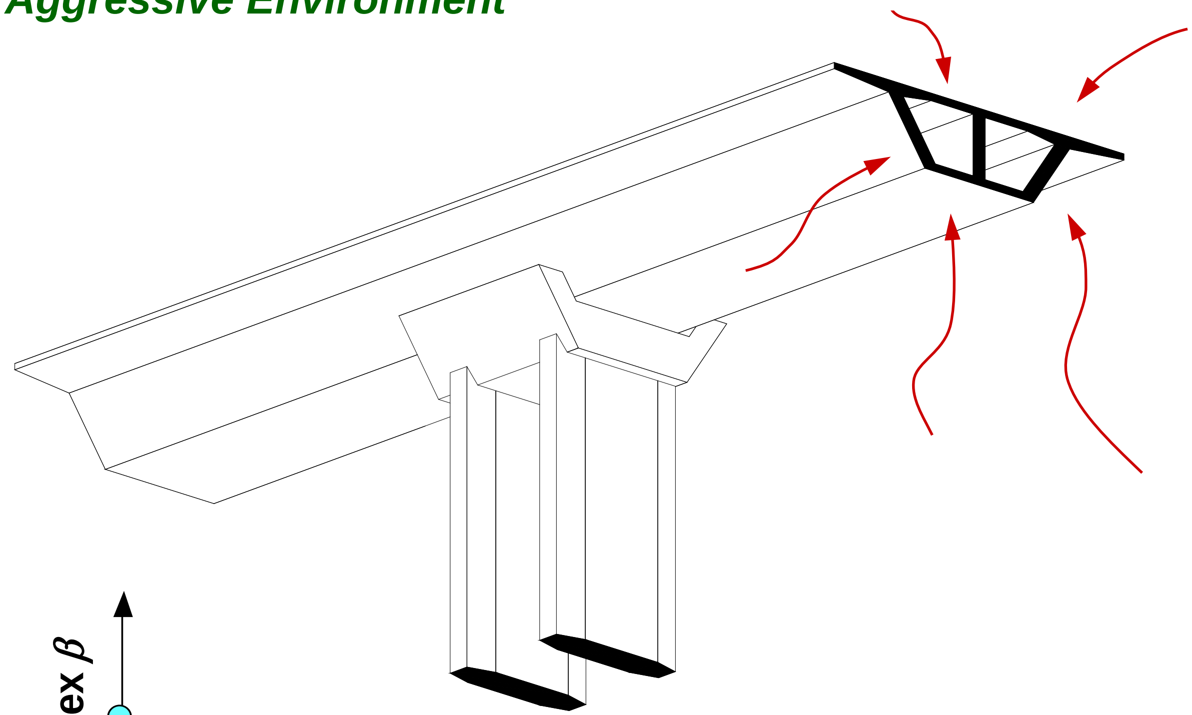
Research Needs

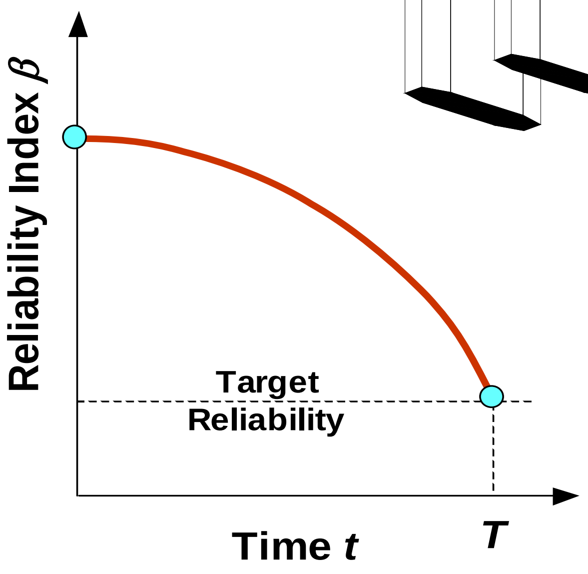
- A durable design cannot be based only on **indirect evaluations** of the effects of structural damage (material quality, concrete cover, etc.), but also needs to take into account the **global effects** of the local damage phenomena on the **overall performance** of the structure.

- A **global approach** to life-cycle assessment and design of concrete bridges under damage should consider, among others:
  - **The quality of structural detailing**
  - **The type of structural scheme**
  - **The interaction of mechanical and environmental stressors**
  - **The effects of maintenance and repair interventions**

Life-Cycle Prediction Models

Aggressive Environment





Structure and Infrastructure Engineering, *i*First, 2013
Structure and Infrastructure Engineering, **7**(1-2), 2011
Structural Safety, **31**, 2009
Structure and Infrastructure Engineering, **4**(5), 2008
Probabilistic Engineering Mechanics, **23**(4), 2008
Structural Engineering International, IABSE, **16**(3), 2006
Journal of Structural Engineering, ASCE, **132**(5), 2006
Journal of Structural Engineering, ASCE, **130**(11), 2004

Research Cooperation

POLITECNICO DI MILANO

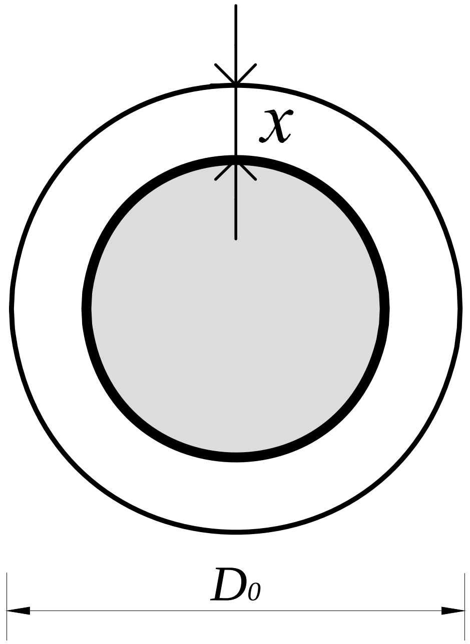
LEHIGH UNIVERSITY

SAPIENZA UNIVERSITÀ DI ROMA

Outline

- Modeling of Structural Damage
- Nonlinear Analysis of Deteriorating Concrete Structures
- Simulation of Diffusion Processes
- Time-variant Performance and Lifetime Assessment
- Effects of Repair Interventions
- Life-Cycle Cost and Maintenance Planning
- Conclusions

Uniform Corrosion



$$p = 2x \qquad \delta = \frac{p}{D_0}$$

$$A_s(\delta) = [1 - \delta_s(\delta)]\, A_{s0}$$

$$A_{s0} = \pi \cdot D_0^2 / 4$$

$$\delta_s = \delta(2 - \delta)$$

Pitting Corrosion

$$R = \frac{x_{\max}}{\bar{x}}$$

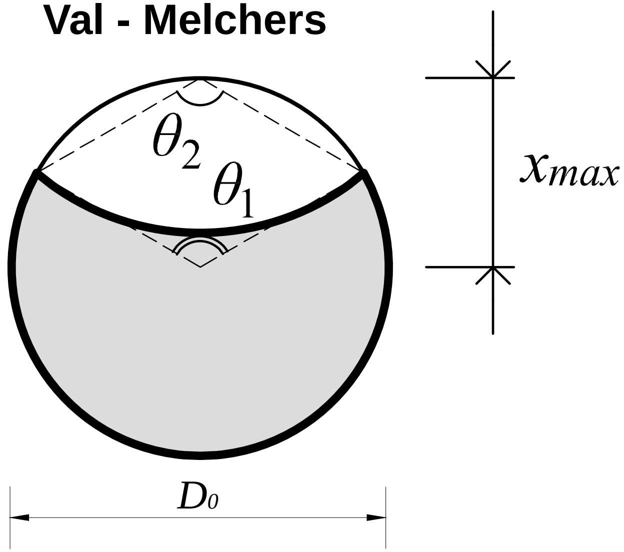
R = 4 – 8 (natural corrosion)

R = 5 – 13 (accelerated corrosion)

$$p = x_{\max}$$

$$\delta = \frac{p}{D_0}$$

Val - Melchers

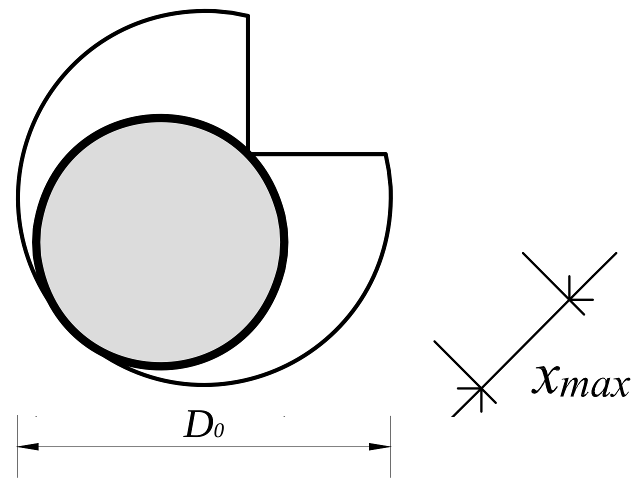


$$\delta_s = \begin{cases} \delta_{s1} + \delta_{s2} & , 0 \le \delta \le 1/\sqrt{2} \\ 1 - \delta_{s1} + \delta_{s2} & , 1/\sqrt{2} < \delta \le 1 \end{cases}$$

$$\delta_{s1} = \frac{1}{2\pi}\left(\theta_1 - 2\beta \left|1 - 2\delta^2\right|\right)$$

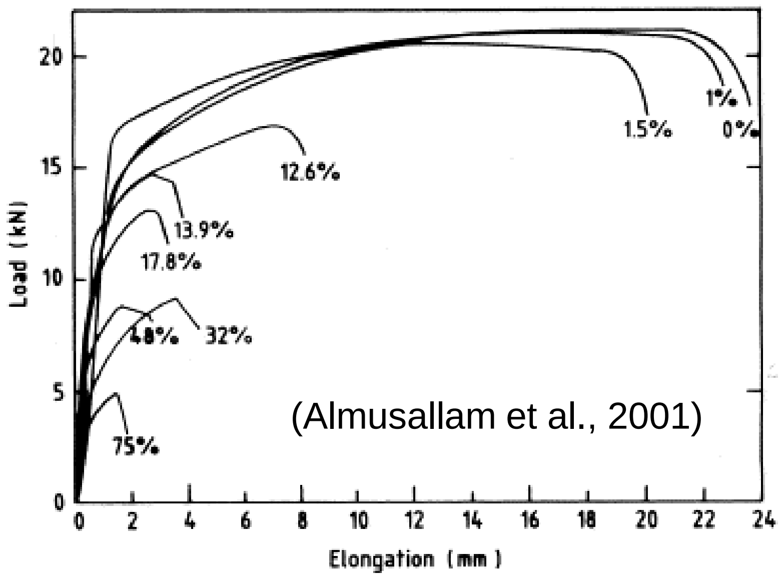
$$\delta_{s2} = \frac{2\delta^2}{\pi}\left(\theta_2 - \beta\right) \qquad \beta = \frac{b_0}{D_0} = 2\delta\sqrt{1-\delta^2}$$

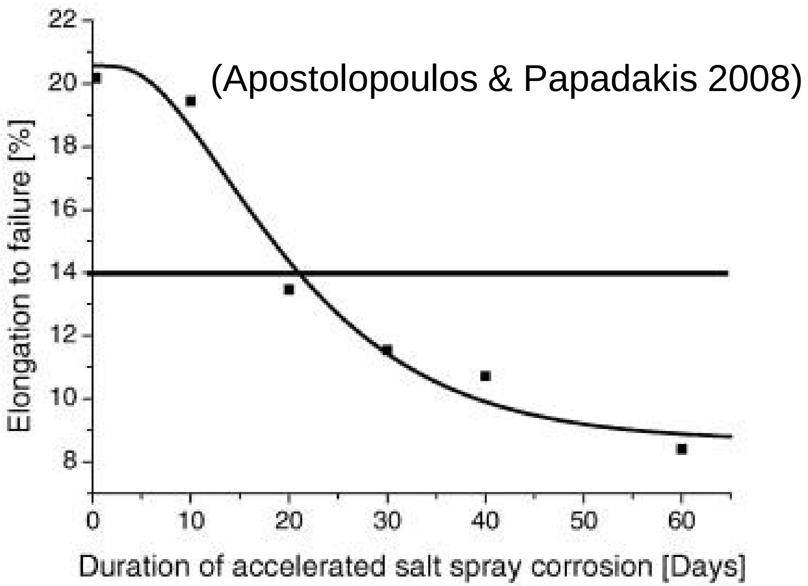
Rodriguez

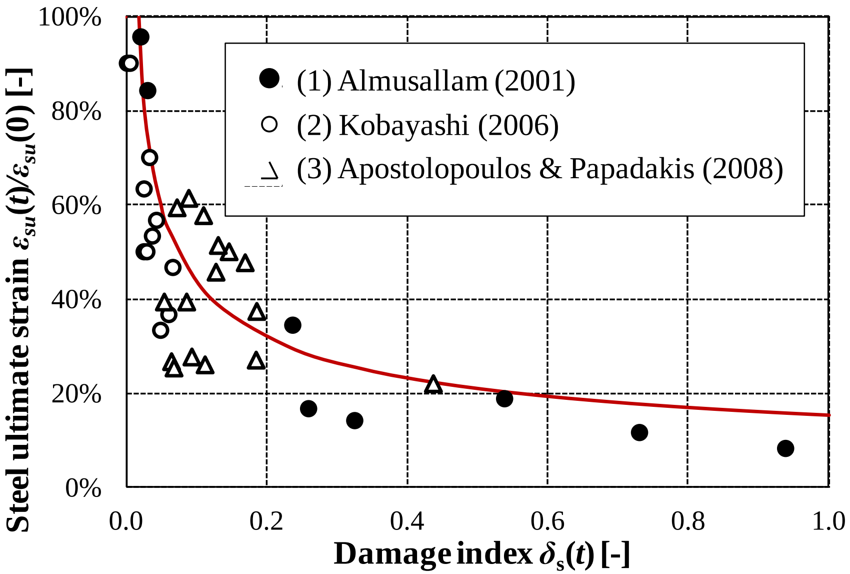


$$\delta_s = \delta(2 - \delta)$$

Reduction of Steel Ductility

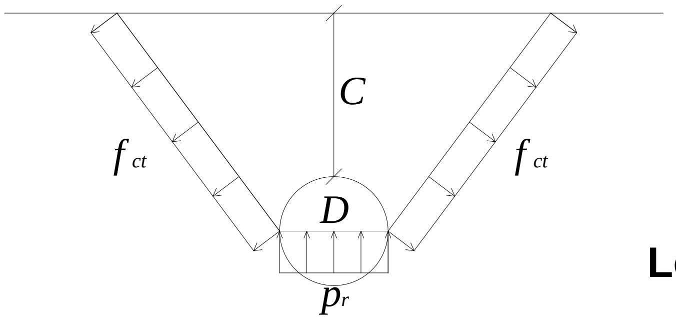






$$\Rightarrow \quad \varepsilon_{su} = \begin{cases} \varepsilon_{su0} & , 0 \le \delta_s < 0.016 \\ 0.1521\delta_s^{-0.4583}\varepsilon_{su0} & , 0.016 < \delta_s \le 1 \end{cases}$$

Deterioration of Concrete (1/2)

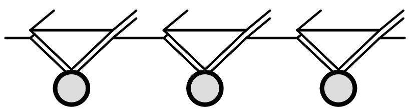


$$A_c = [1-\delta_c(\delta)]\, A_{c0}$$

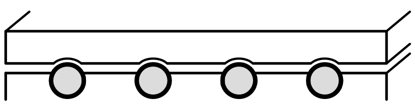
$$f_c = [1-\delta_c(\delta)]\, f_{c0}$$

Longitudinal cracking and spalling of concrete cover

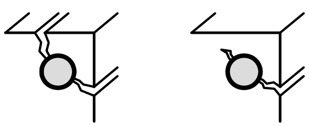
Scaling

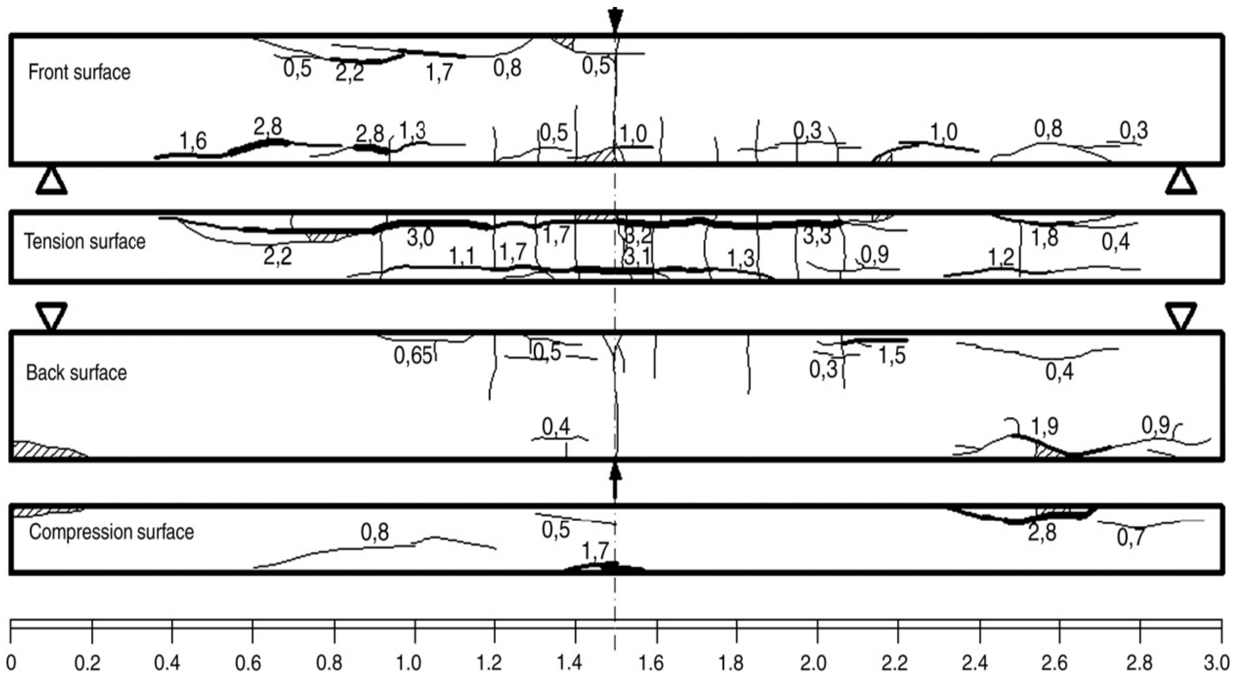


Delamination



Border effects





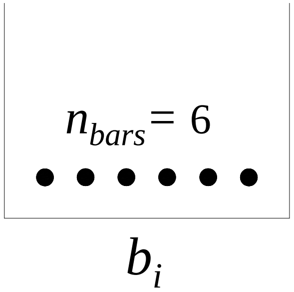
[Zhang *et al.* 2009]

Deterioration of Concrete (2/2)

$$f_c = [1 - \delta_c(\delta)]\, f_{c0}$$

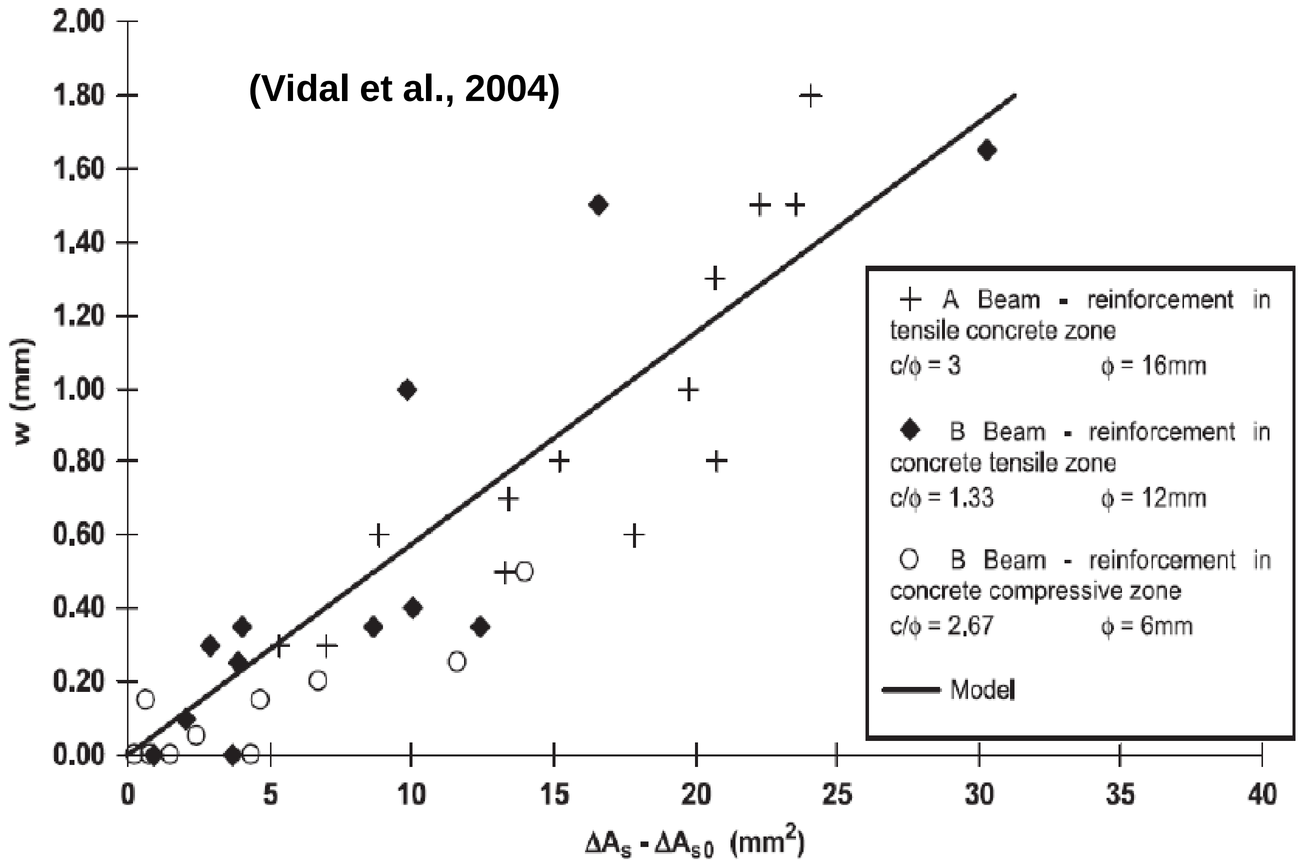
(Vecchio & Collins, 1986)

$$f_c = \frac{f_{c0}}{1 + \kappa \dfrac{\varepsilon_\perp}{\varepsilon_{c0}}}$$



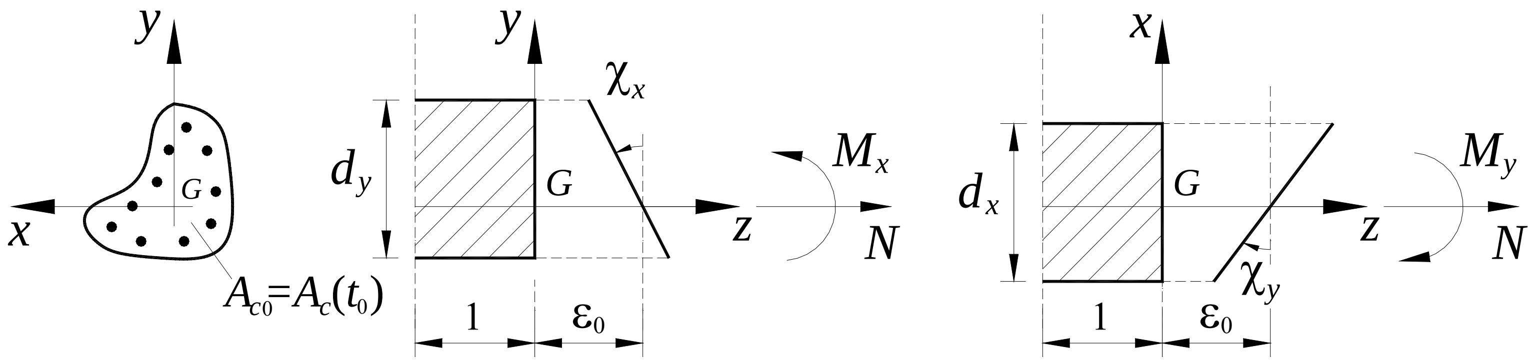
$$\varepsilon_\perp = \frac{\Delta b}{b_i} = \frac{n_{bars} w}{b_i}$$

$$w = \kappa_w (\delta_s - \delta_{s0}) A_{s0}$$



$$\delta_{s0} = 1 - \left[1 - \frac{R}{D_0}\left(7.53 + 9.32\frac{c_0}{D_0}\right)\times 10^{-3}\right]^2$$

STRUCTURAL ANALYSIS OF DAMAGED REINFORCED CONCRETE SECTIONS

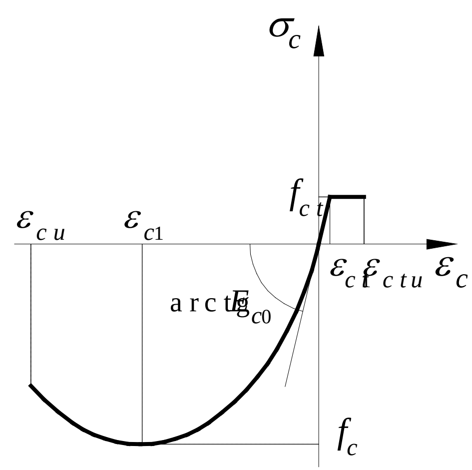


$$\mathbf{r}(t) = \mathbf{H}(t)\,\mathbf{e}(t)$$

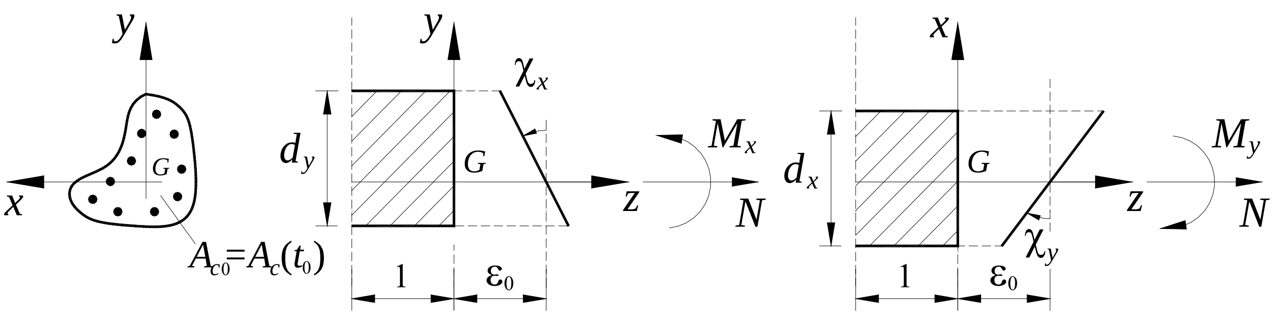
$\mathbf{r} = \mathbf{r}(t) = [\,N \;\; M_x \;\; M_y\,]^T$ vector of the stress resultants at the time instant t

$\mathbf{e} = \mathbf{e}(t) = [\varepsilon_0 \;\; \chi_x \;\; \chi_y\,]^T$ vector of the global strains at the time instant t

$$\mathbf{H}(t) = \mathbf{H}_c(t) + \mathbf{H}_s(t) = \int_{A_c} E_c(x,y,t)\,\mathbf{b}(x,y)^T\,\mathbf{b}(x,y)\,\delta_c'(x,y,t)\,dA + \sum_k E_{sk}(t)\,\mathbf{b}_k^T\mathbf{b}_k\,\delta_{sk}'(t)\,A_{sk}$$

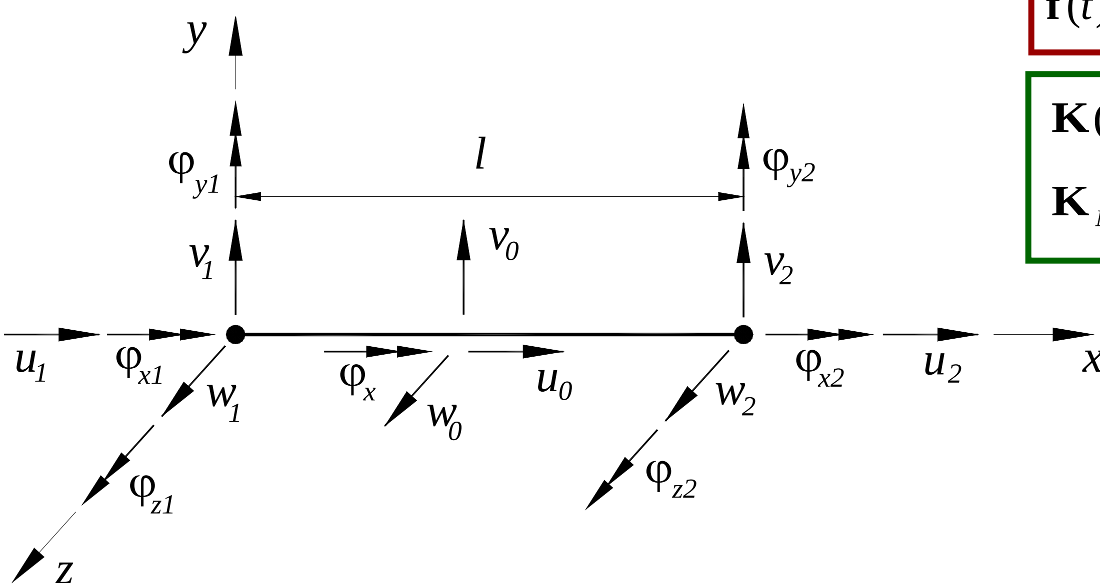


Deteriorating R.C. Beam Element



$$\mathbf{r} = \mathbf{r}(t) = [\ N \ \ M_x \ \ M_y\ ]^T$$
$$\mathbf{e} = \mathbf{e}(t) = [\varepsilon_0 \ \ \chi_x \ \ \chi_y\ ]^T$$
$$\mathbf{r}(t) = \mathbf{H}(t)\,\mathbf{e}(t)$$

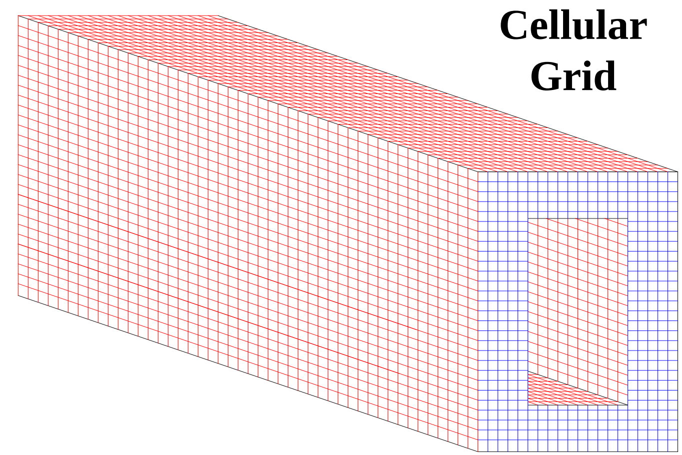
$$\mathbf{H}(x,t) = \mathbf{H}_c(x,t) + \mathbf{H}_s(x,t)$$



$$\mathbf{f}(t) = \mathbf{K}(t)\,\mathbf{s}(t)$$

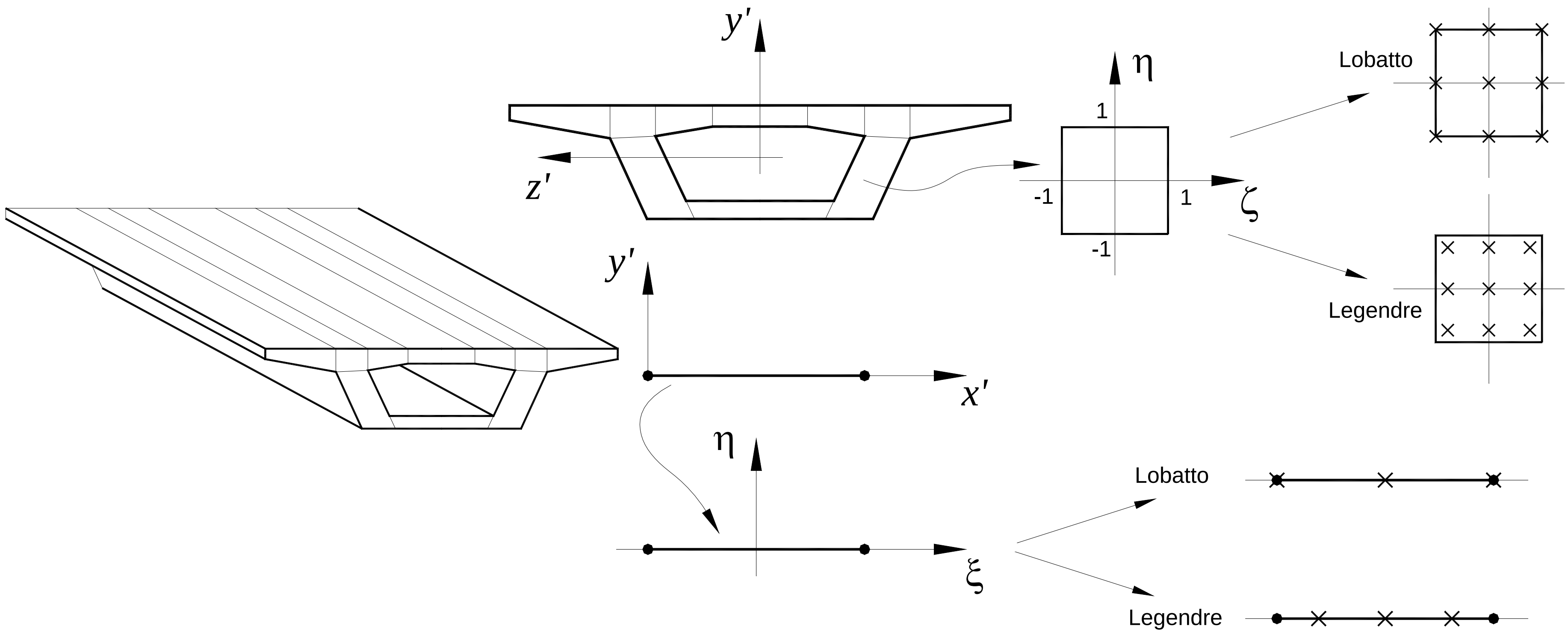
$$\mathbf{K}(t) = \mathbf{K}_M(t) + \mathbf{K}_G(t)$$
$$\mathbf{K}_M(t) = \int_0^l \mathbf{B}^T \mathbf{H}(t)\,\mathbf{B}\,dx = \mathbf{K}_c(t) + \mathbf{K}_s(t)$$

Cellular Grid



Biondini F., Bontempi F., Frangopol D.M., Malerba P.G., 2004. Cellular Automata Approach to Durability Analysis of Concrete Structures in Aggressive Environments. *Journal of Structural Engineering*, ASCE, **130**(11), 1724-1737.

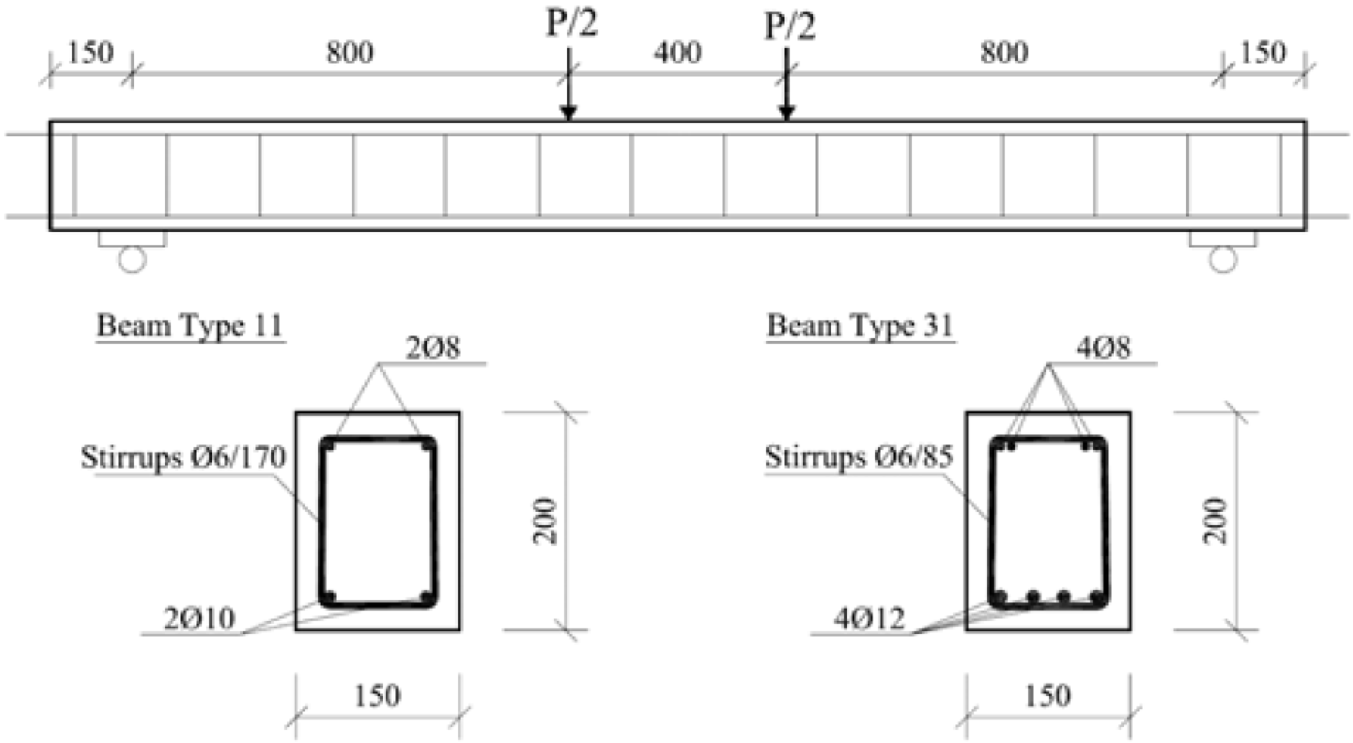
Isoparametric Sub-Domains



$$I = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} f(\xi,\eta,\zeta)\, d\xi\, d\eta\, d\zeta = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{n} w_i w_j w_k\, f(\xi_i,\eta_j,\zeta_j)$$

Numerical Validation – Beams

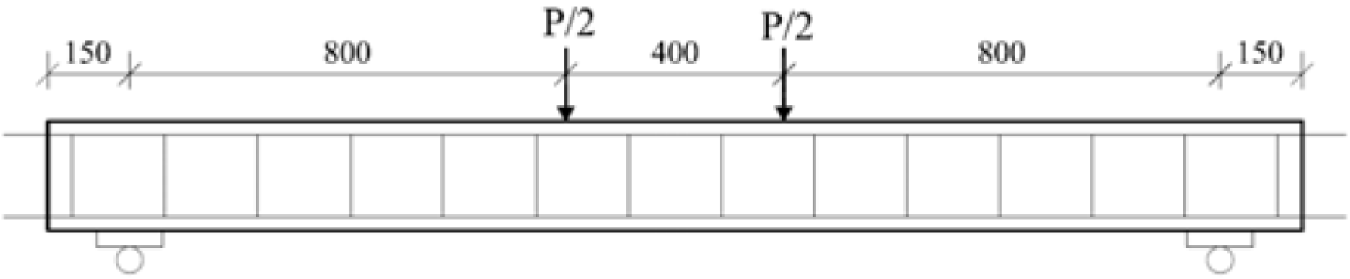
(Rodriguez et al., 1997)



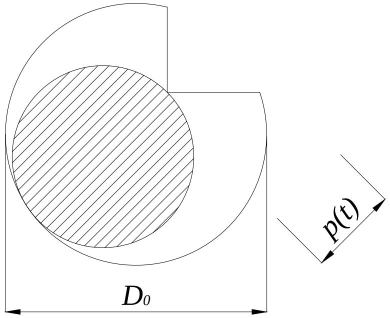
Parameter	Beam 111	Beams 114-116	Beam 311	Beams 313-316
f_{cc} [MPa]	50	34	49	37
f_{ct} [MPa]	4.1	3.1	4.1	3.2
E_c [GPa]	37.3	33.8	37.1	34.5

Parameter	Φ 8 bars	Φ10 bars	Φ12 bars
f_{sy} [MPa]	615	575	585
f_{su} [MPa]	673	655	673
E_s [GPa]	210	210	210

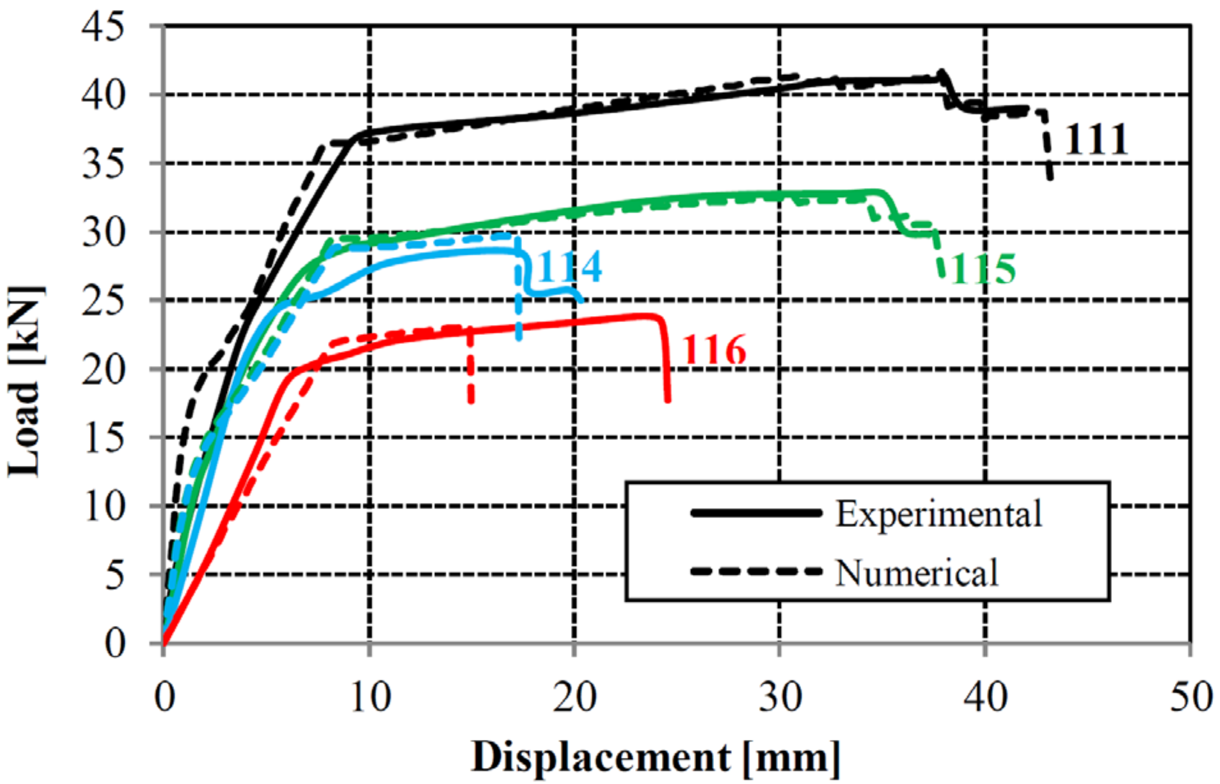
Numerical Validation – Corrosion

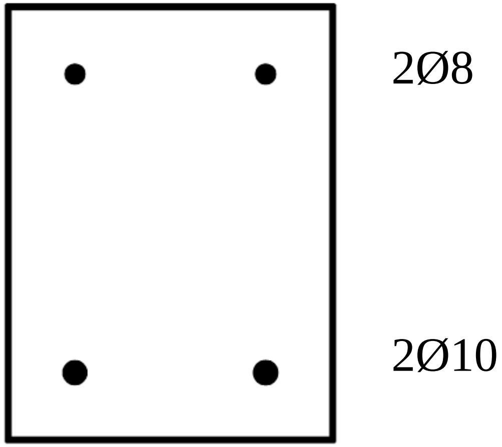


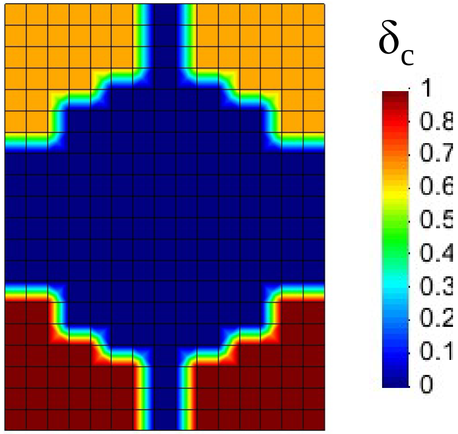
	Mean penetration depth [mm] (maximum value)		
Beam	Tension bars	Compression bars	Stirrups
114	0.45 (1.1)	0.52	0.39 (3.1)
115	0.36 (1.0)	0.26	0.37 (3.0)
116	0.71 (2.1)	0.48	0.66 (5.0)
313	0.30 (1.3)	0.20	0.35 (2.8)
314	0.48 (1.5)	0.26	0.50 (4.0)
316	0.42 (1.8)	0.37	0.54 (4.3)



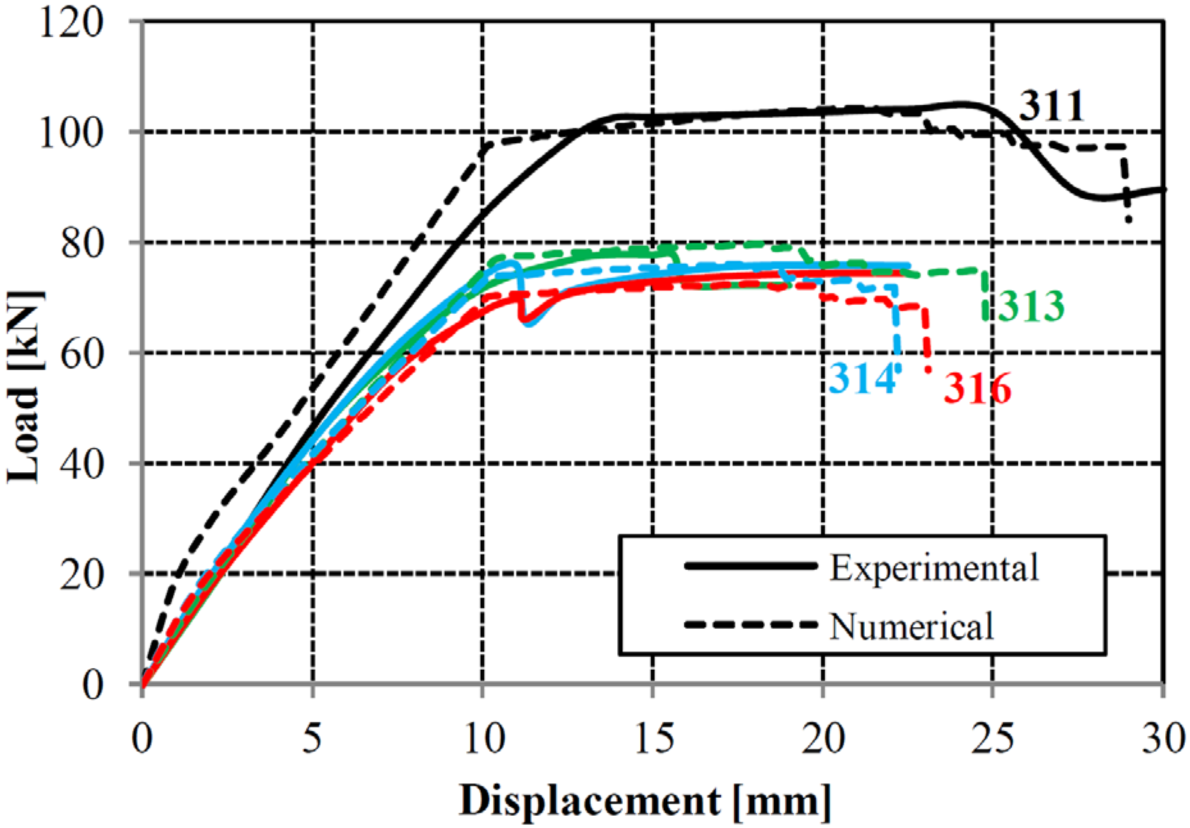
Numerical Validation – Results

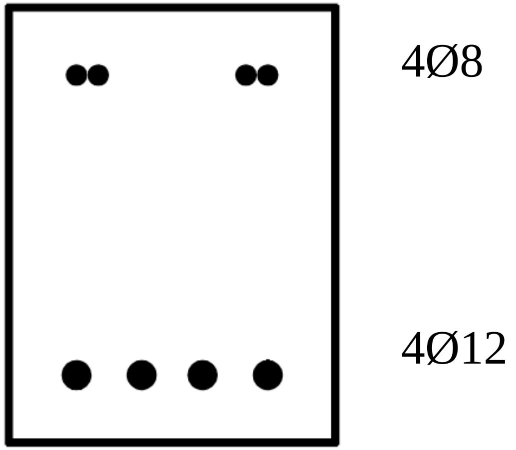


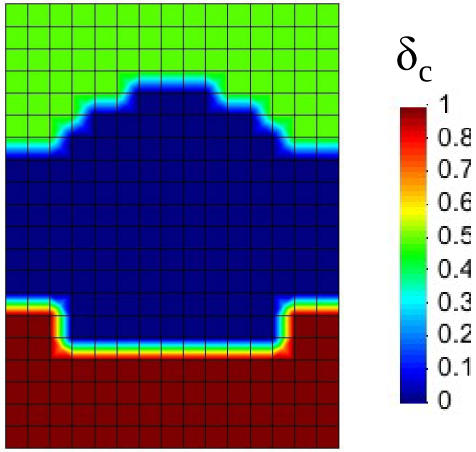




Numerical Validation – Results

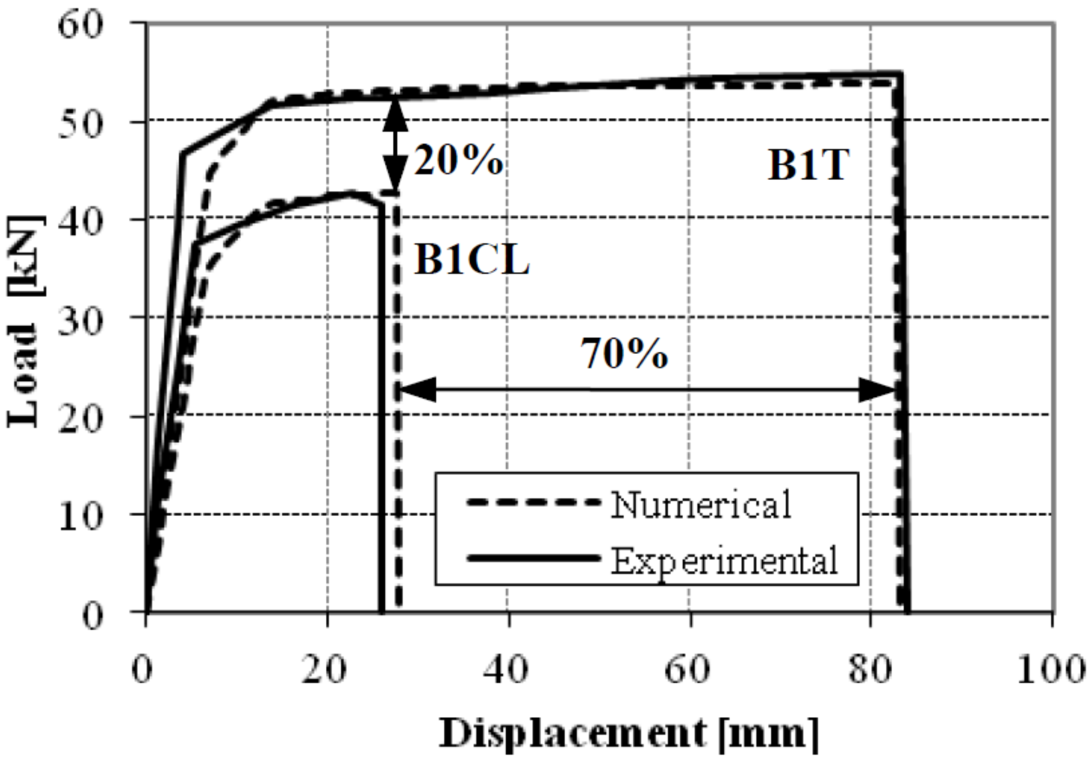






Validation under Natural Corrosion

- Simply supported beam L=2.80m under concentrated load at midspan
- Cross-section 150x280mm, 2ϕ16 + 2ϕ12, cover 10 mm
- Material strengths f_c = 65 MPa and f_y = 500 MPa
- Exposed to natural environment for 14 years



(Castel et al., 2000)

B1T = No corrosion

B1CL= Corroded beam
(Average corrosion level 20%)

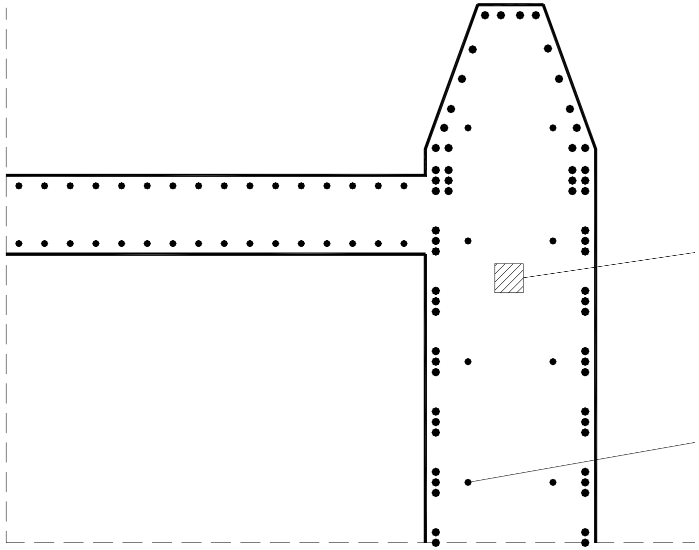
Damage Modeling

Damage Indices of the Materials

$0 \le \delta(t) \le 1$

0 = Undamaged

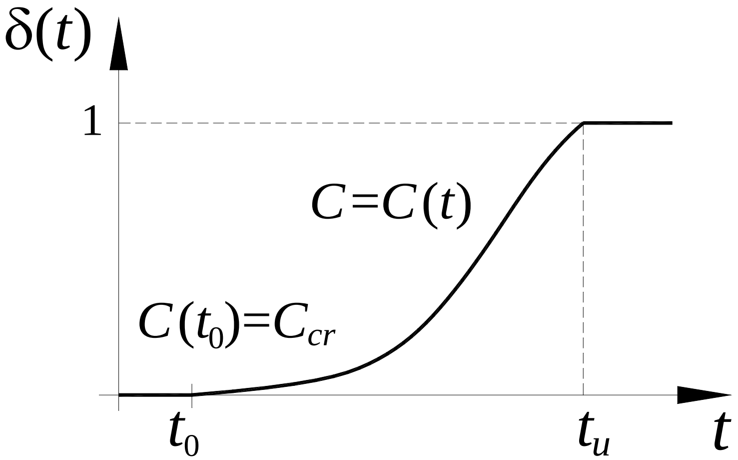
1 = Full damaged



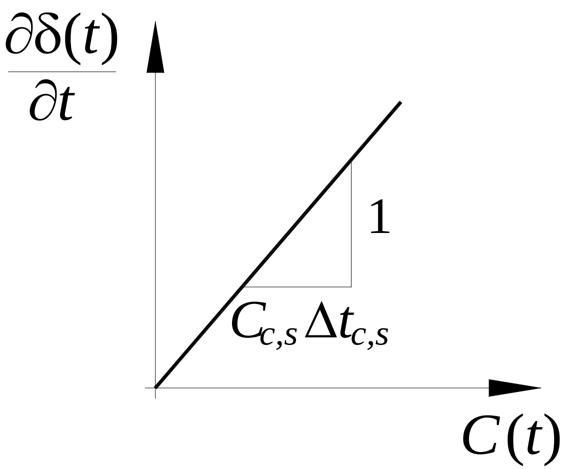
$f_c = [1-\delta_c(t)]\, f_{c0}$

$dA_c(t) = [1-\delta_c(t)]\, dA_{c0}$

$A_s(t) = [1-\delta_s(t)]\, A_{s0}$

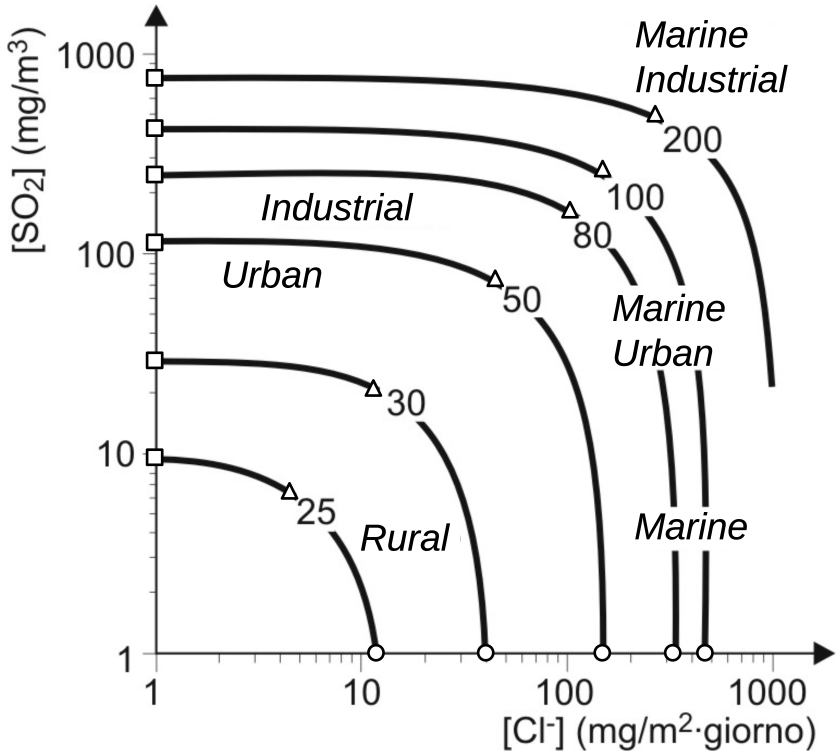


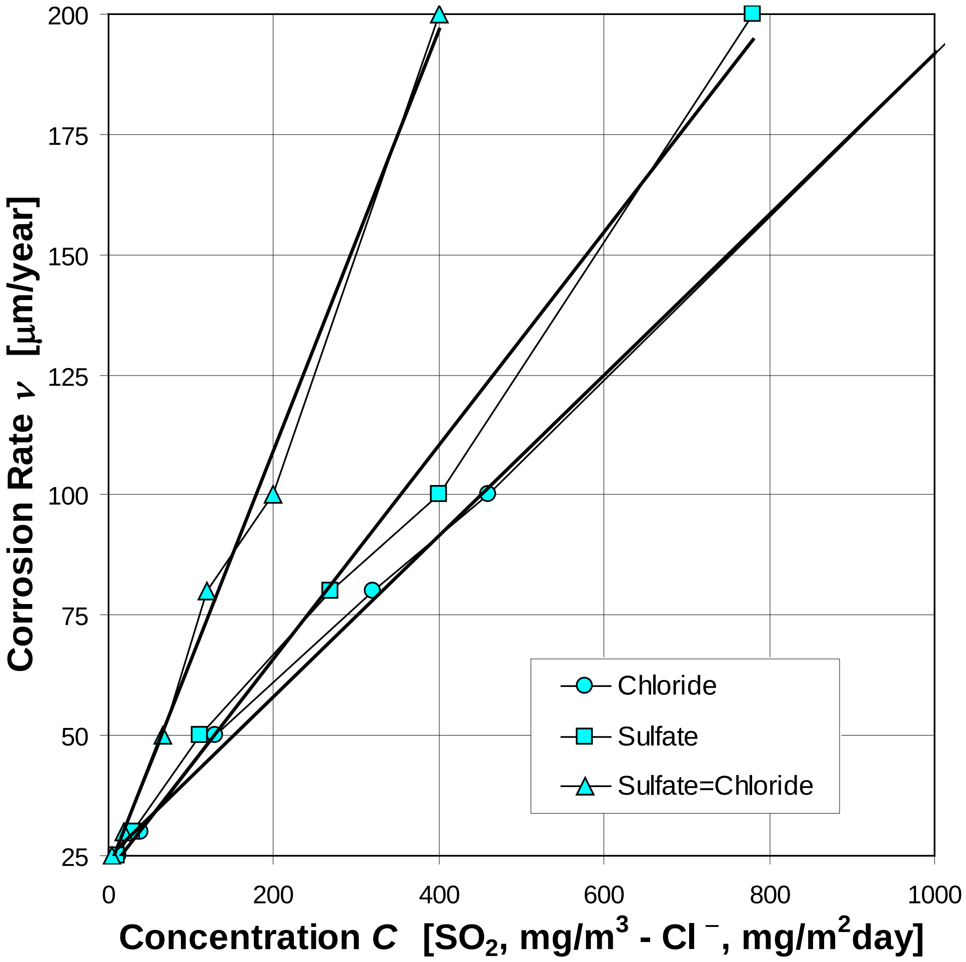
Rate of Damage



Corrosion Rate

Corrosion Rate [μm/year] vs Concentration of Aggressive Agents





(Adapted from: Pedeferri & Bertolini, 1996)

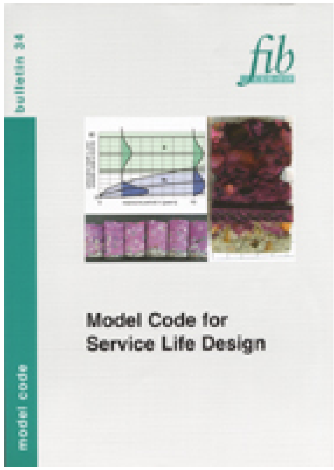
Simulation of the Diffusion Process

➢ **Fick's second law (1D, 2D, 3D)**

$$\nabla^2 C = \frac{1}{D} \cdot \frac{\partial C}{\partial t}$$

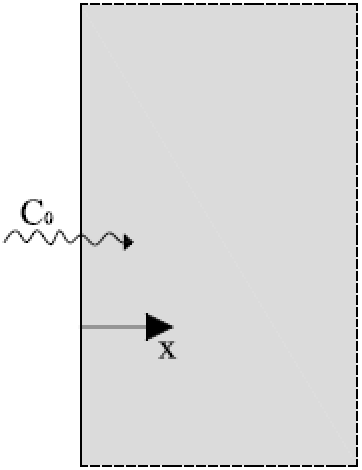
C = Concentration
D = Diffusivity
t = Time

➢ **Simplified approach – Solution of the 1D problem**

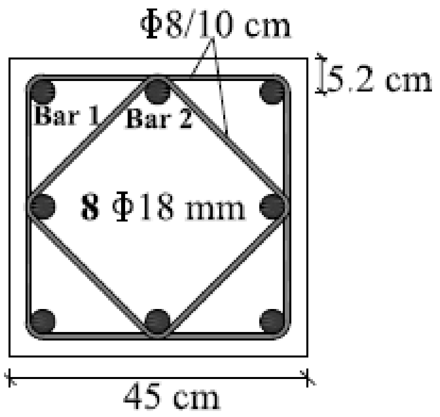


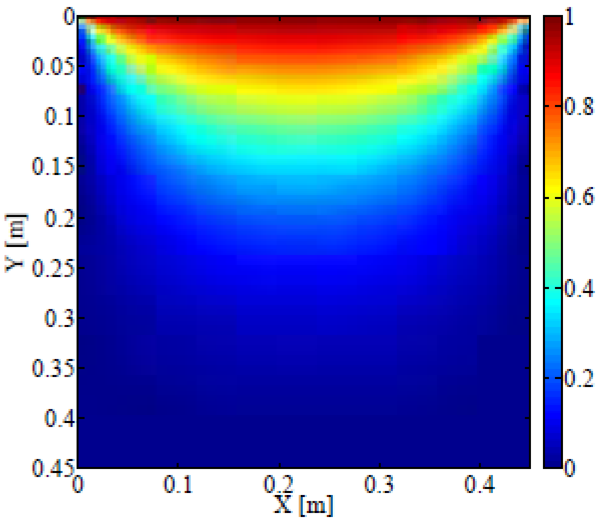
$$C(x,t) = C_0 \left[1 - erf\left(\frac{x}{2\sqrt{D\,t}} \right) \right]$$

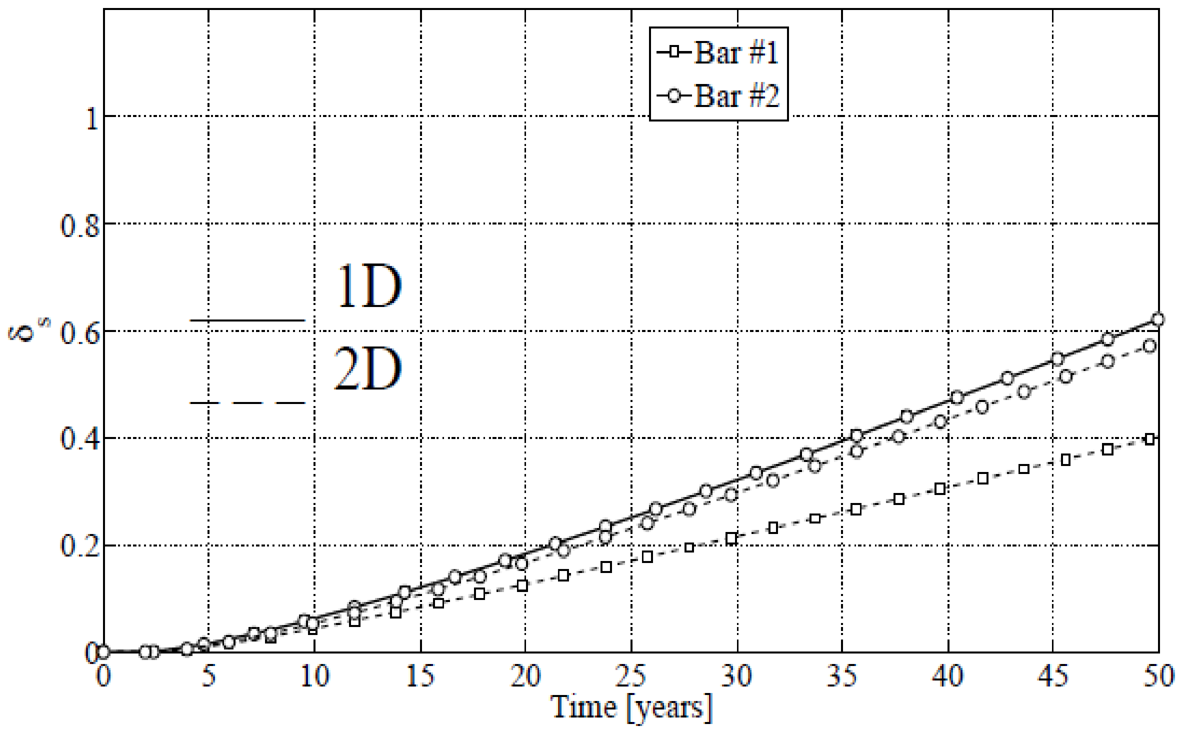
Model Code for Service Life Design
fib Bulletin No. 34, 2006



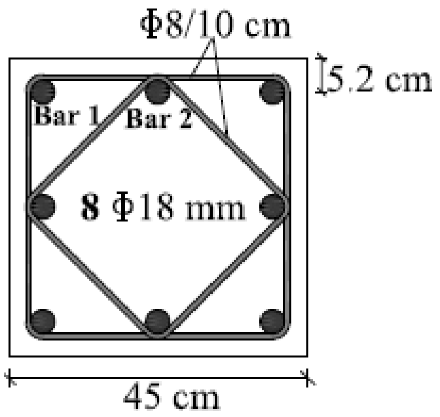
Validation of the Diffusion Model

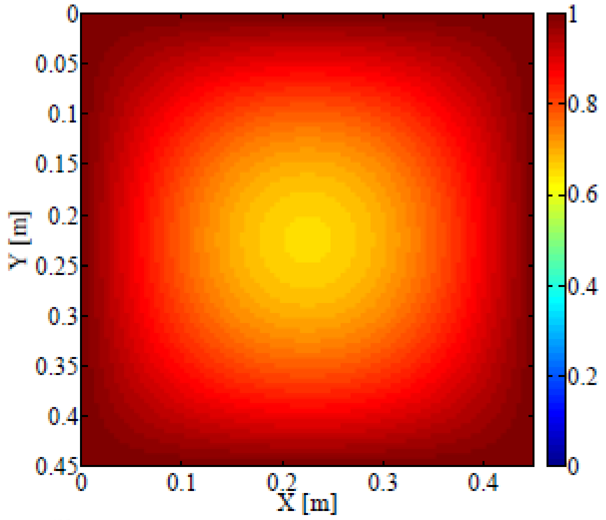


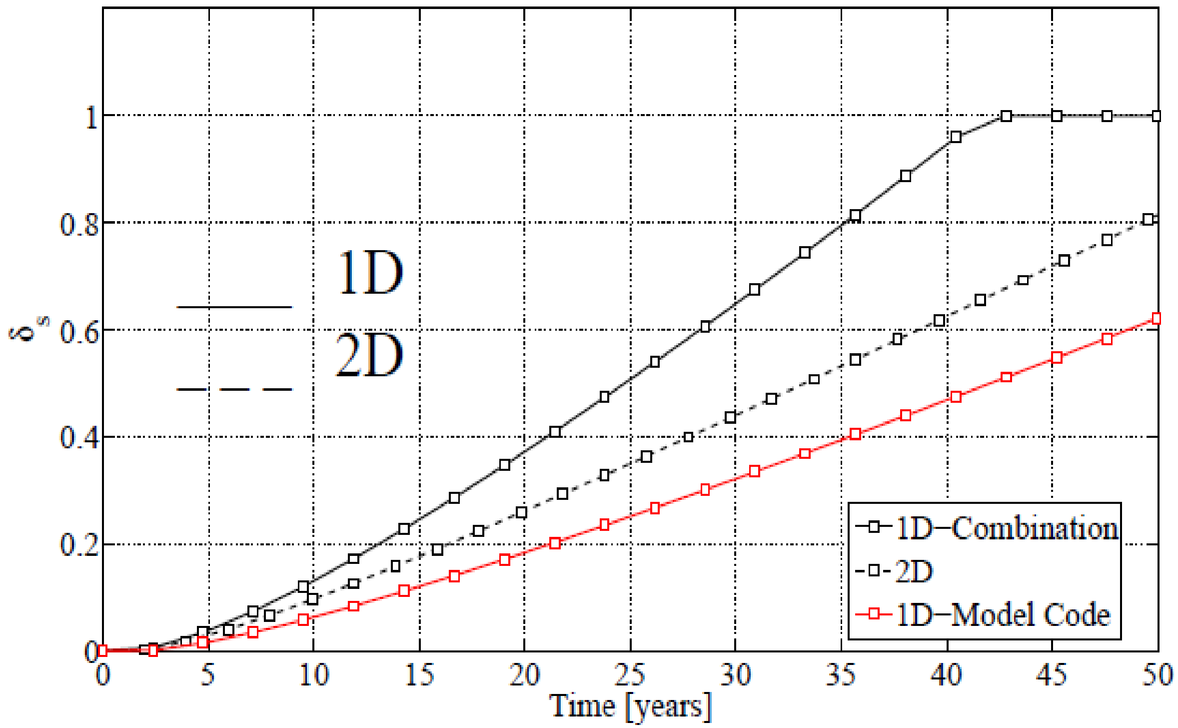




Validation of the Diffusion Model



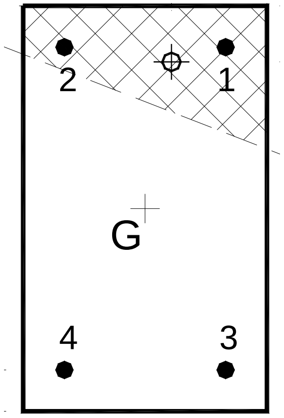




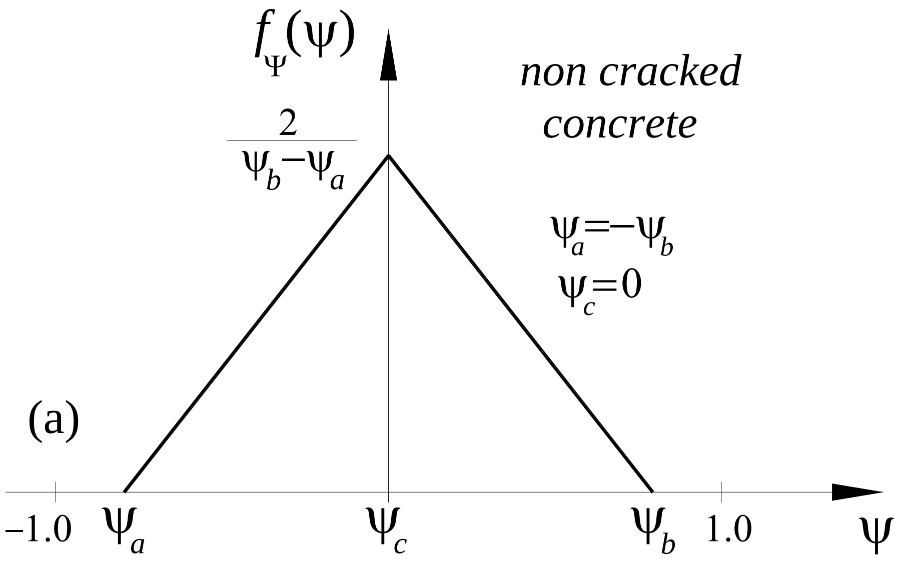
Coupling between Diffusion and Damage

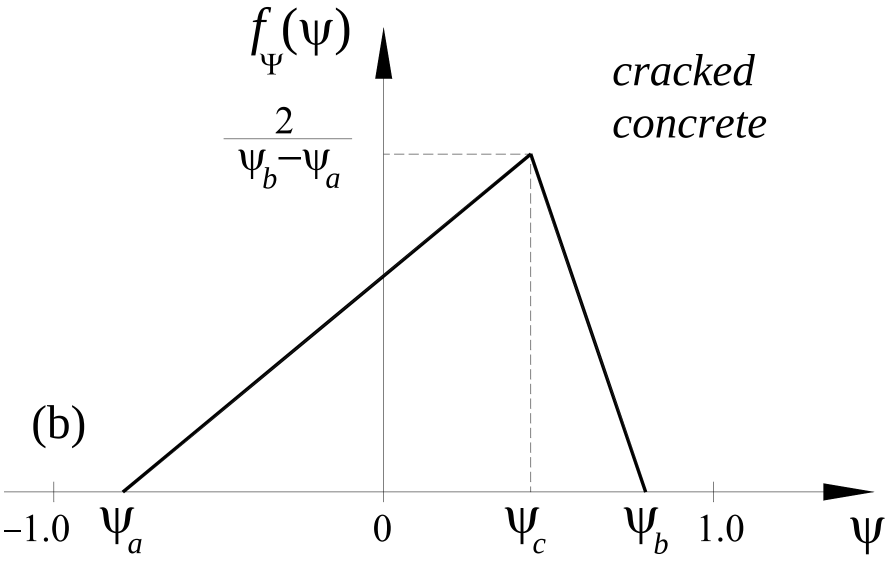
Stochastic Effects and Evolutionary Rule

$$D = (1+\Psi)\cdot D_0$$

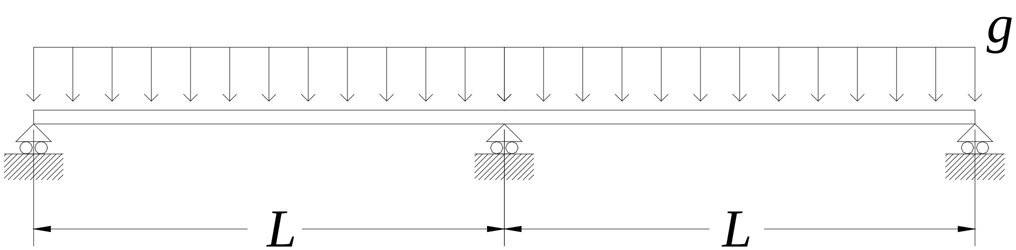


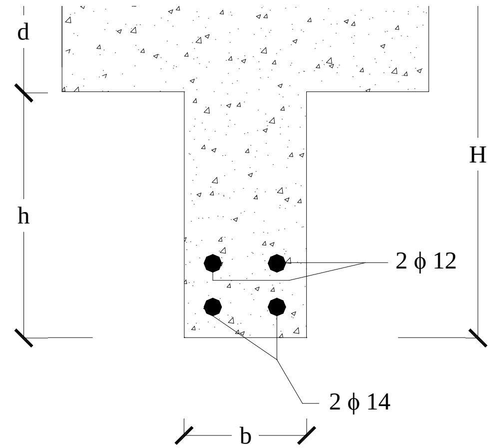
- (A) Symmetrical Ψ–Distributions in *Uncracked Concrete*
- (B) Skewed Ψ–Distributions in *Cracked Concrete*



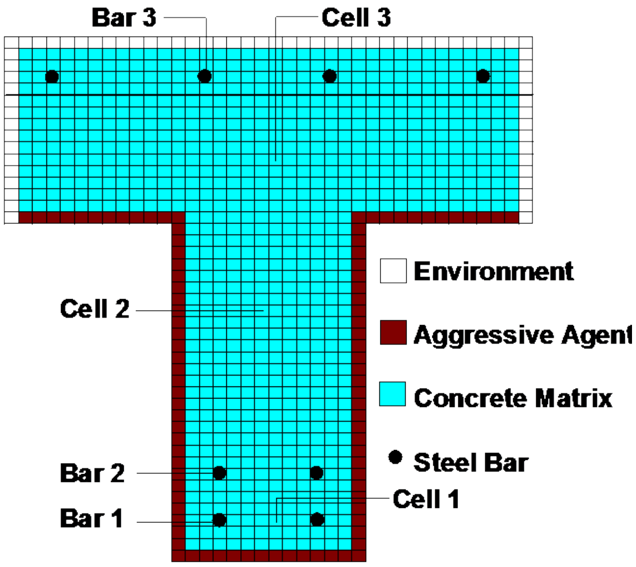


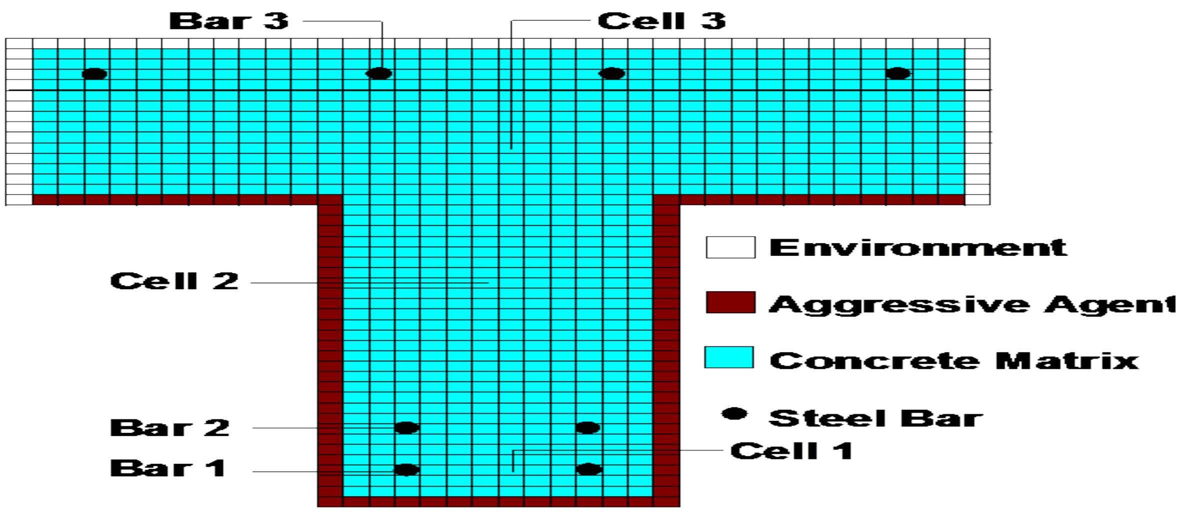
Continuous T-Beam



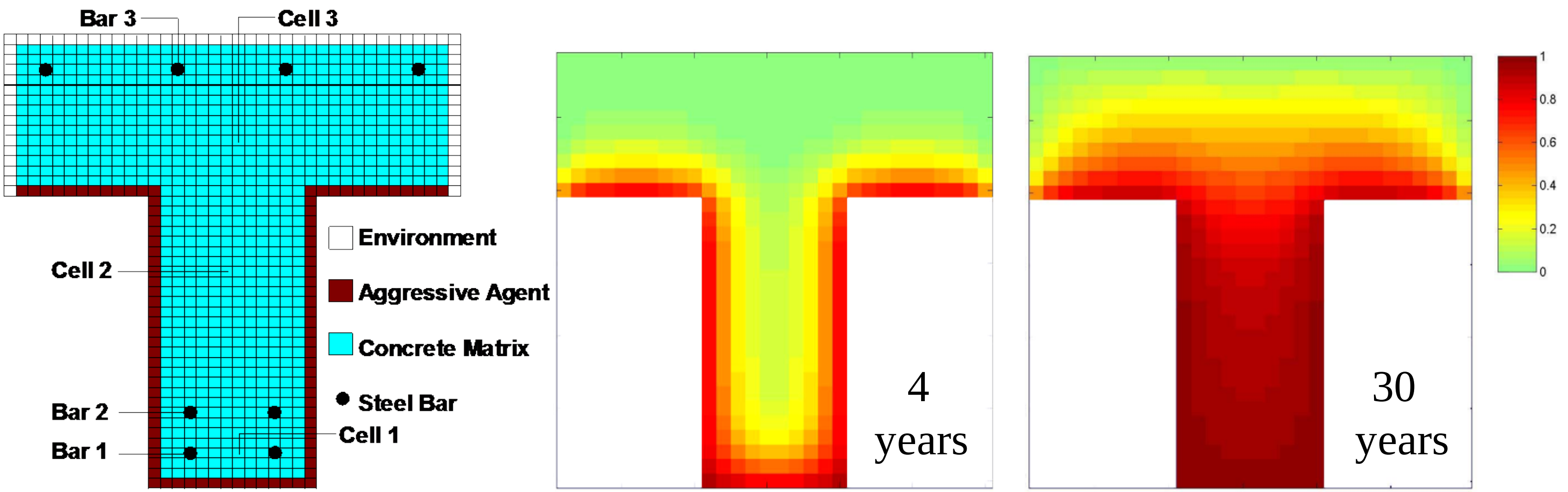


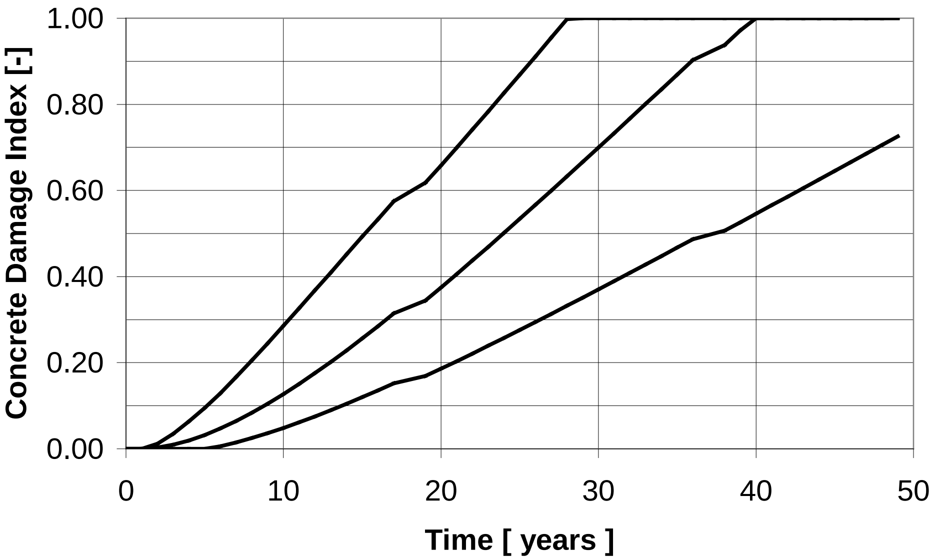
L=3.00 m
H=0.40 m
h=0.25 m
B=0.40 m
b=0.15 m
g=10 kN/m



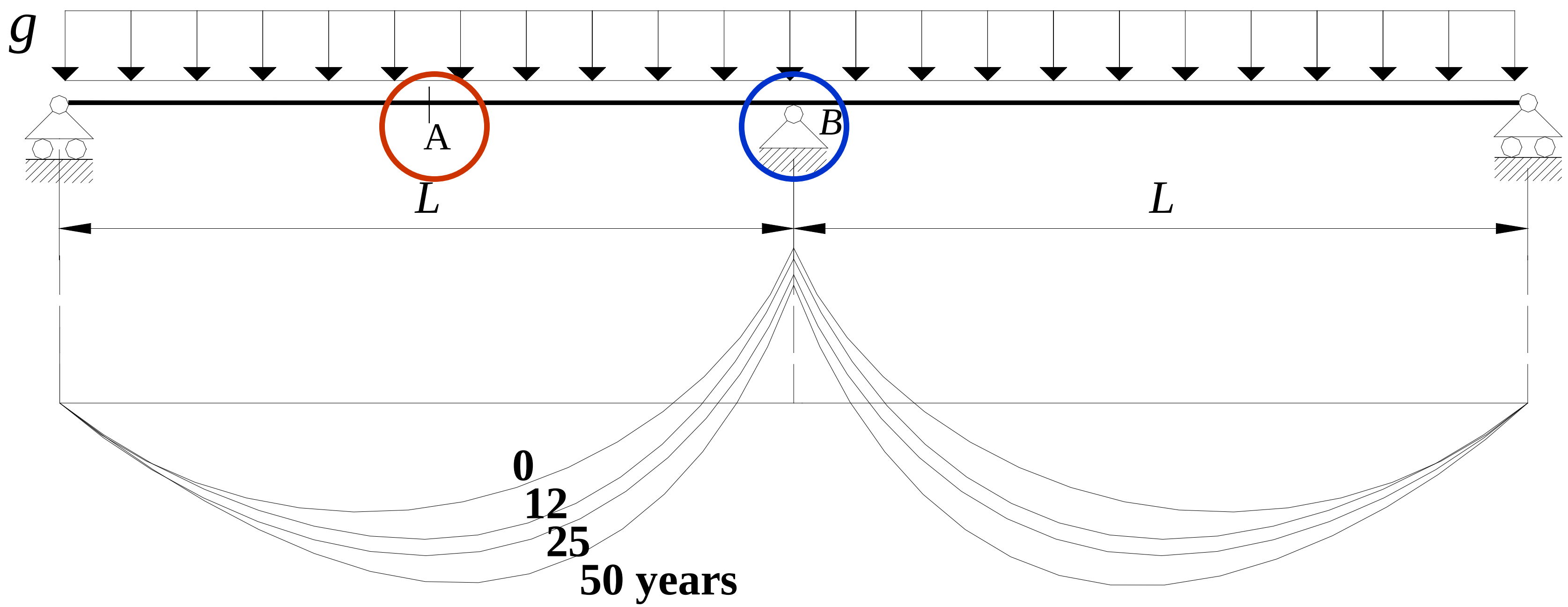


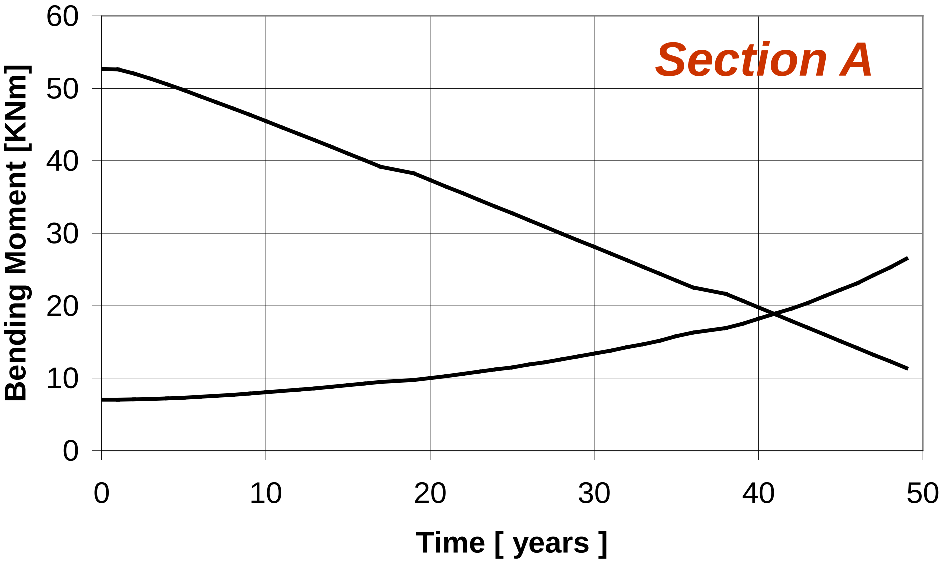
Diffusion and Mechanical Damage





Life-Cycle Performance





Section B

Safety Factor and Load Multiplier

- A structure is **safe** when the effects of the **applied actions *S*** are no larger than its **resistance *R***:

$$R \geq S$$

or when the ***safety factor*** **Θ = *R* / *S*** is no lower than unity:

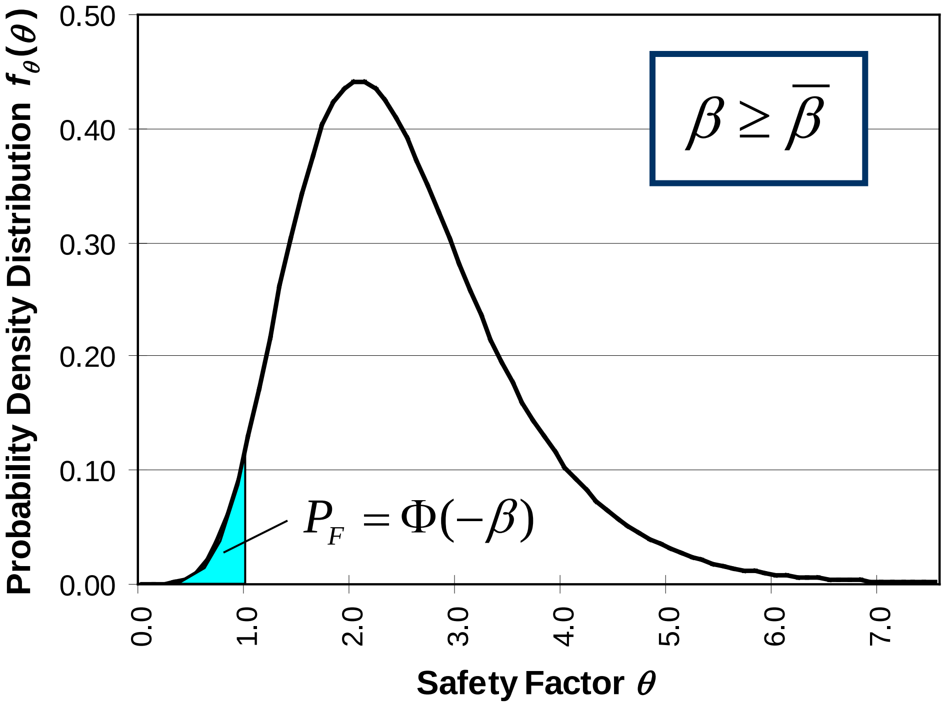
$$\Theta \geq 1$$

Probability of Failure and Reliability Index

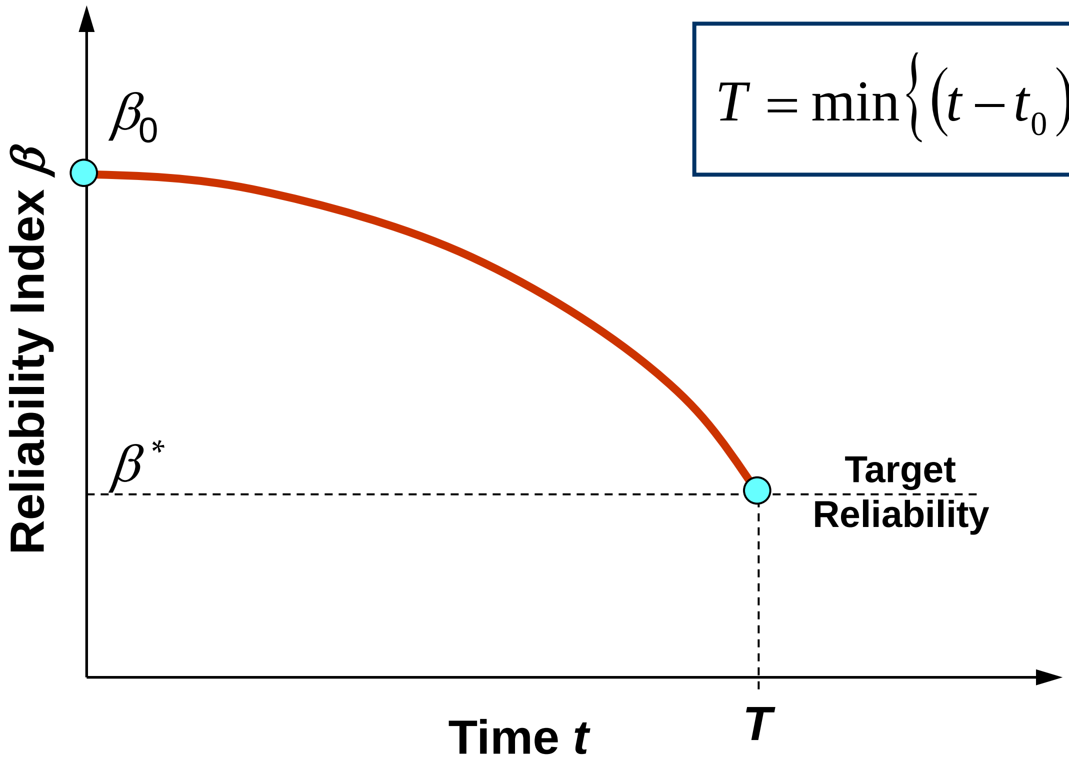
➢ The **probability of failure** P_F, or the **reliability index** β, can be evaluated by the integration of the **density function** $f_\Theta(\theta)$ within the **failure domain** D:

$$P_F = P(\Theta < 1) = \int_D f_\Theta(\theta)\,\mathrm{d}\theta = \Phi(-\beta)$$

$$D = \left\{ \theta \,\middle|\, \theta < 1 \right\}$$



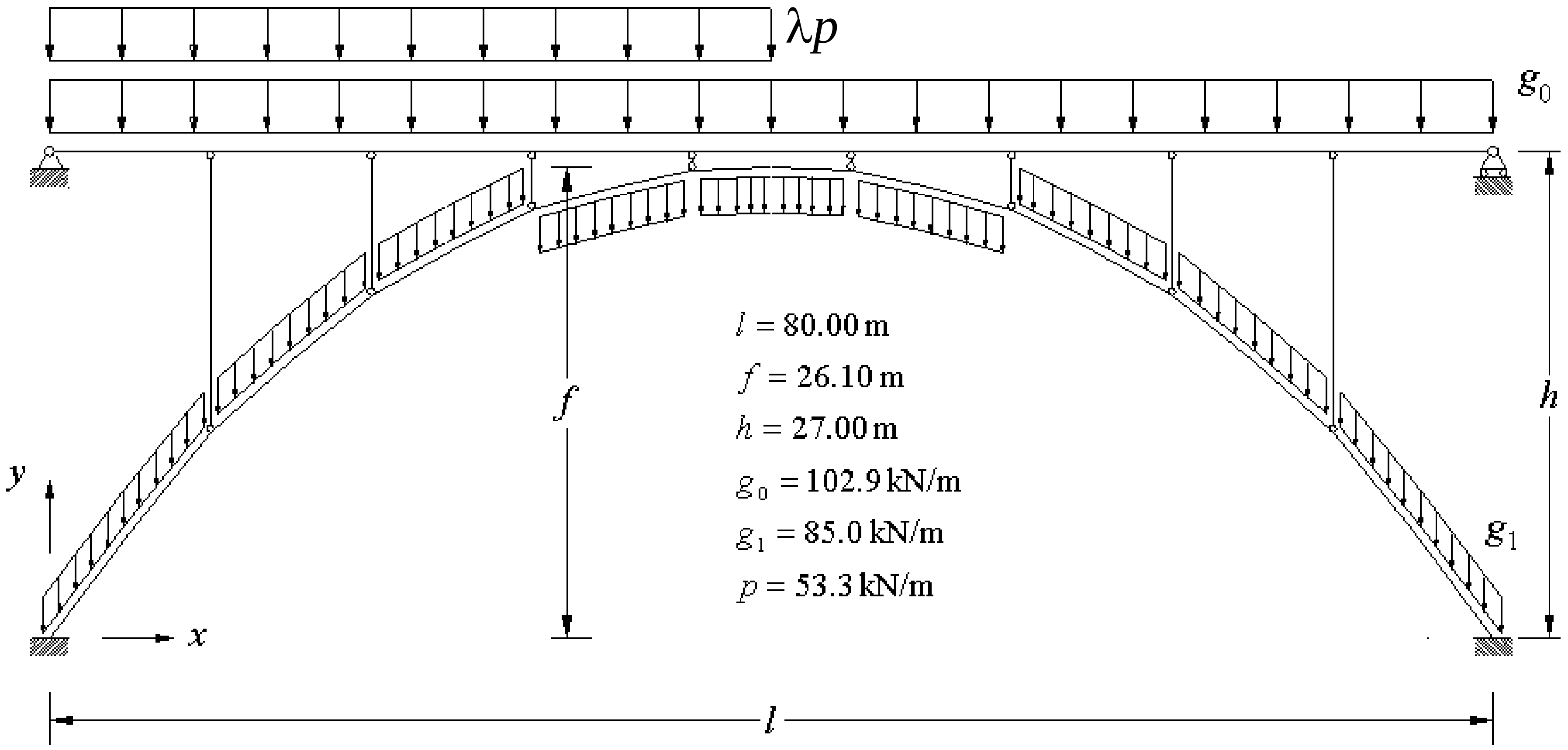
Residual Lifetime



$$T = \min\left\{ (t - t_0) \,\middle|\, \beta \geq \beta^* \right\}$$

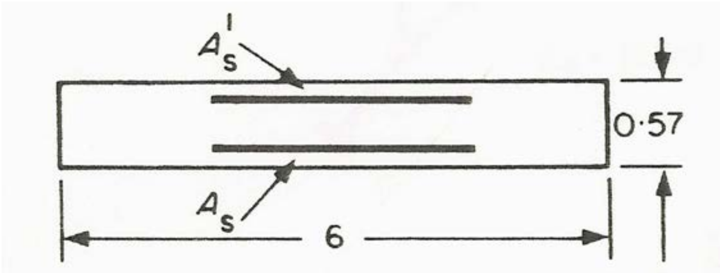
Arch Bridge

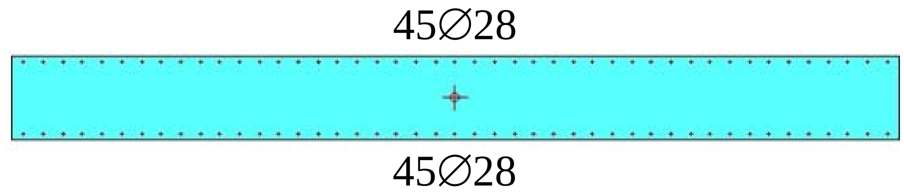
Structural Model

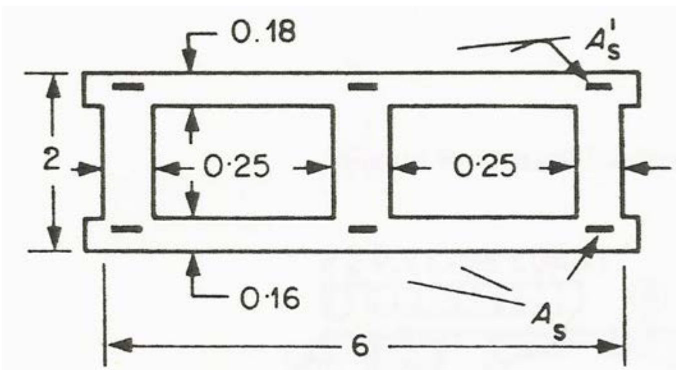


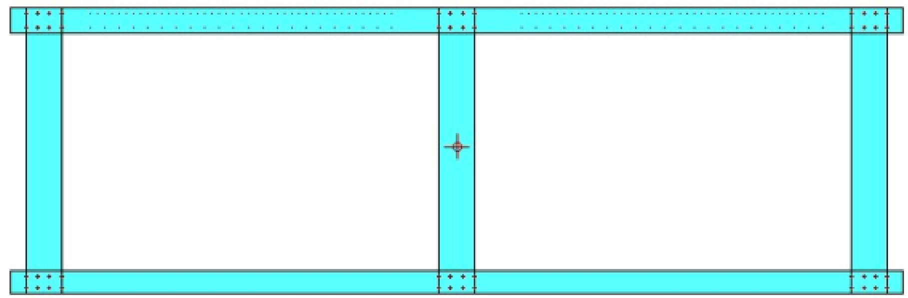
Biondini, F. & Frangopol, D.M. 2008. Probabilistic Limit Analysis and Lifetime Prediction of Concrete Structures, *Structure and Infrastructure Engineering*, **4**(5), 399-412.

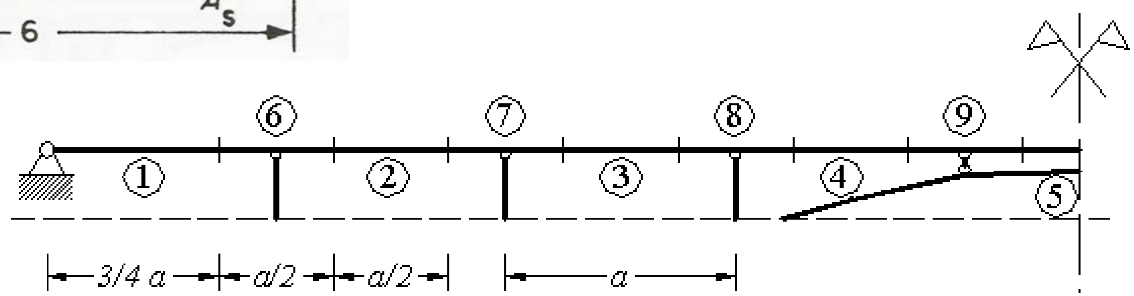
Characteristics of the Cross-Sections





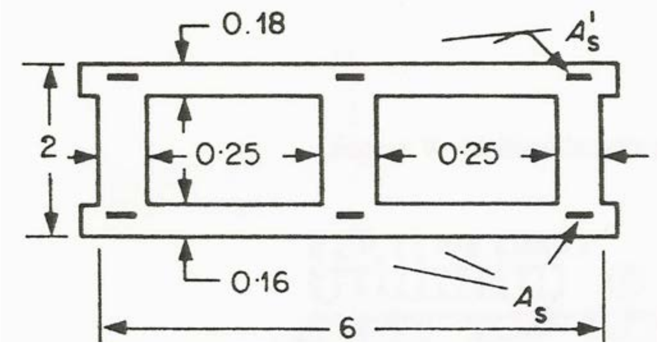


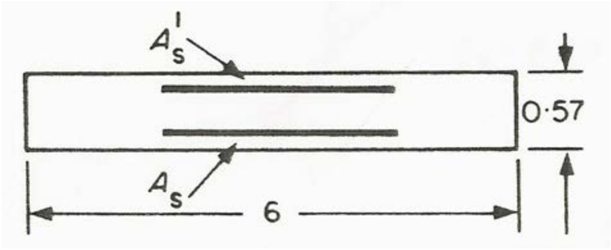


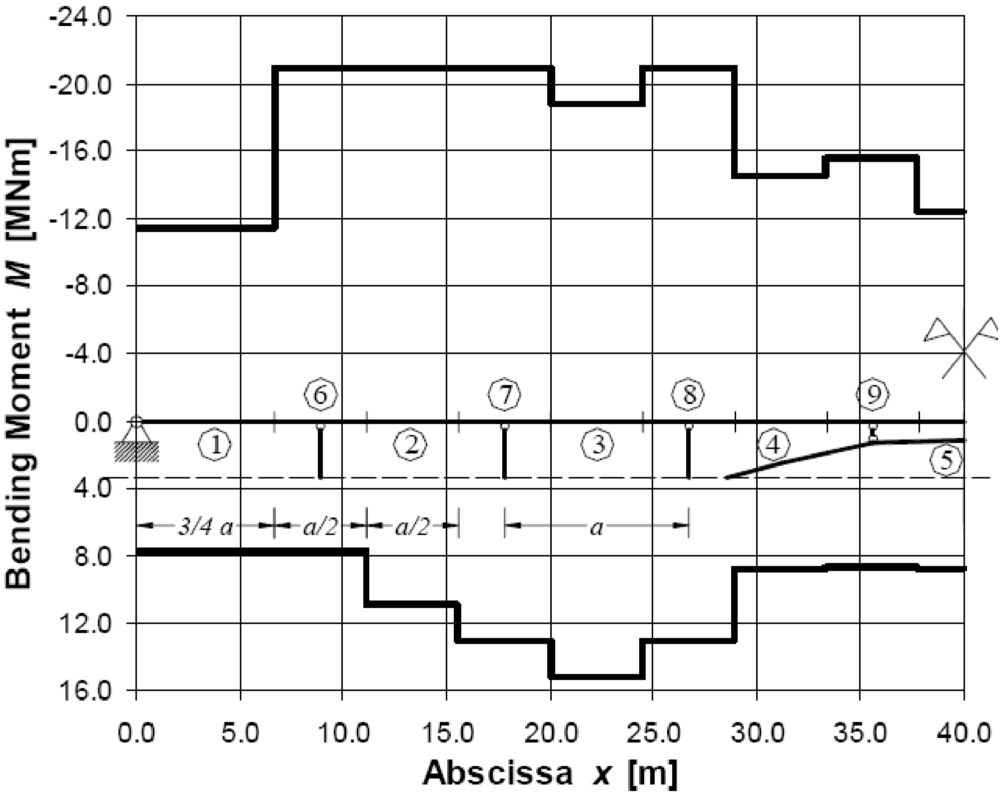


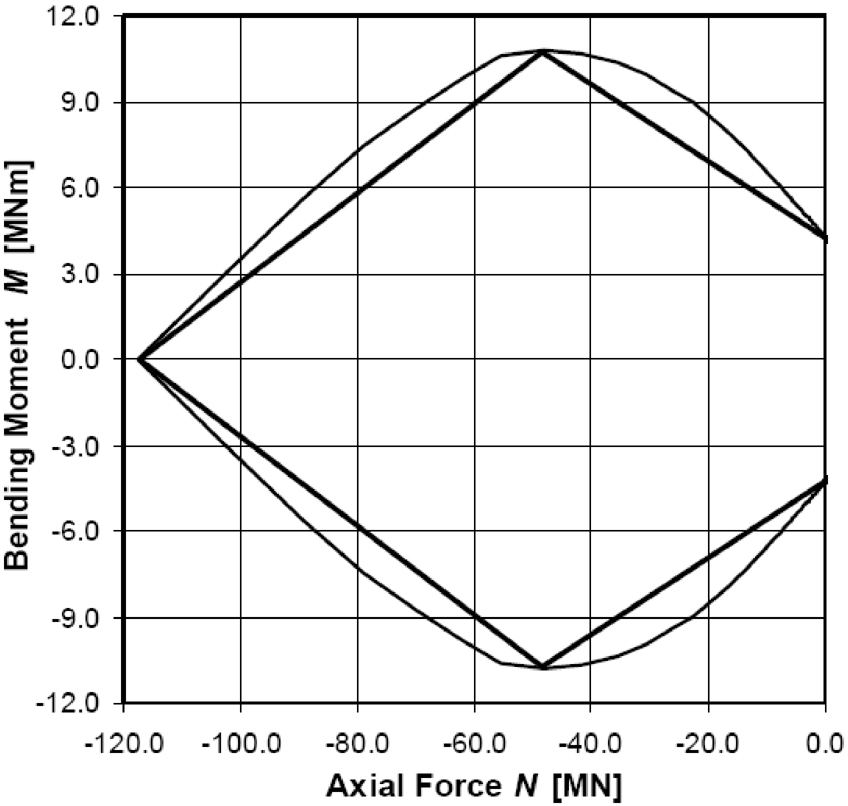
Span	1	2	3	4	5	6	7	8	9
A_s'	21∅28 130∅8	48∅28 130∅8	42∅28 130∅8	30∅28 130∅8	24∅28 130∅8	48∅28 130∅8	48∅28 130∅8	45∅28 130∅8	33∅28 130∅8
A_s	21∅28	30∅28	42∅28	24∅28	24∅28	21∅28	36∅28	27∅28	24∅28

Characteristics of the Cross-Sections

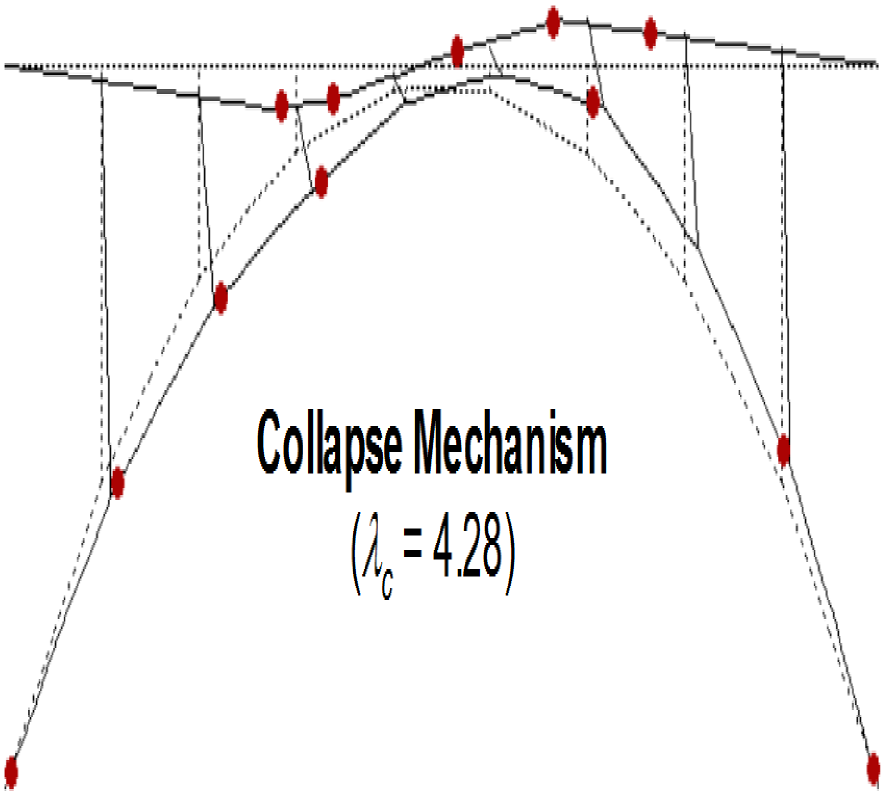


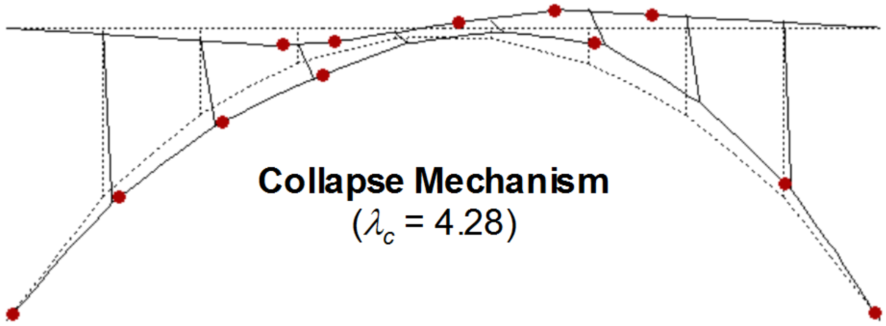




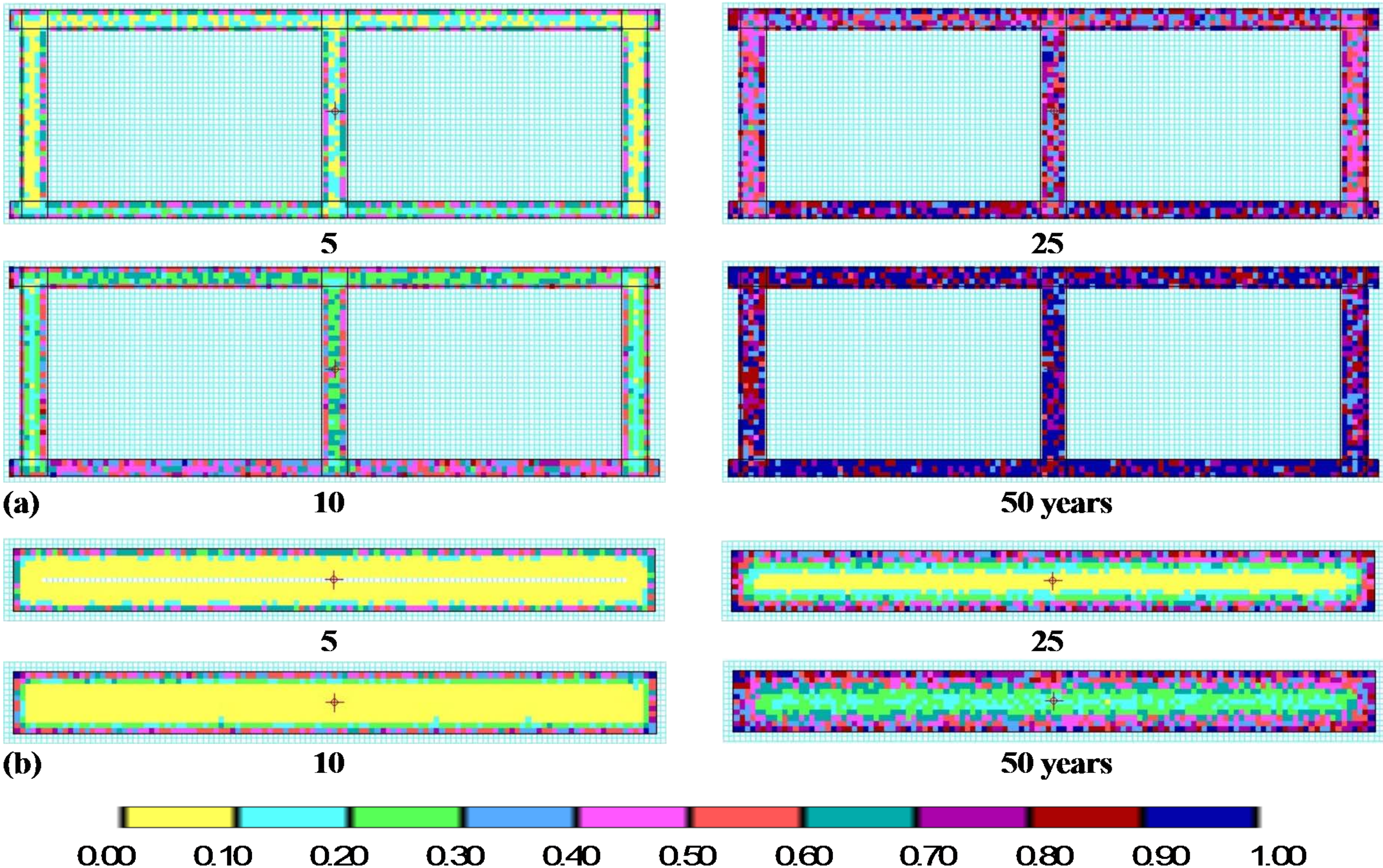


Limit Analysis of the Bridge



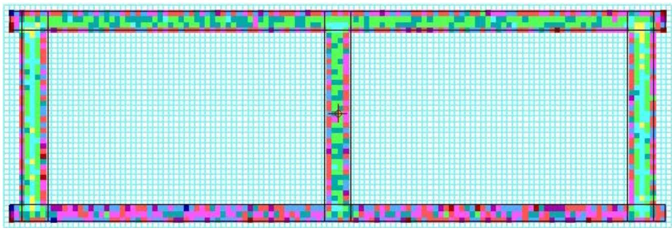


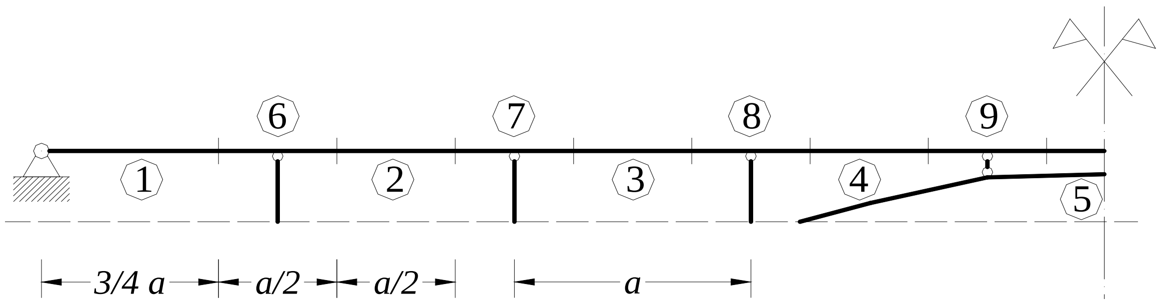
Concentration Maps



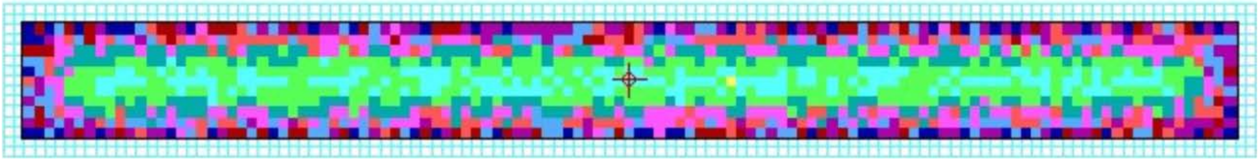
Maps of concentration $C(x,t)/C_0$ of the aggressive agent. (a) Beam (b) Arch.

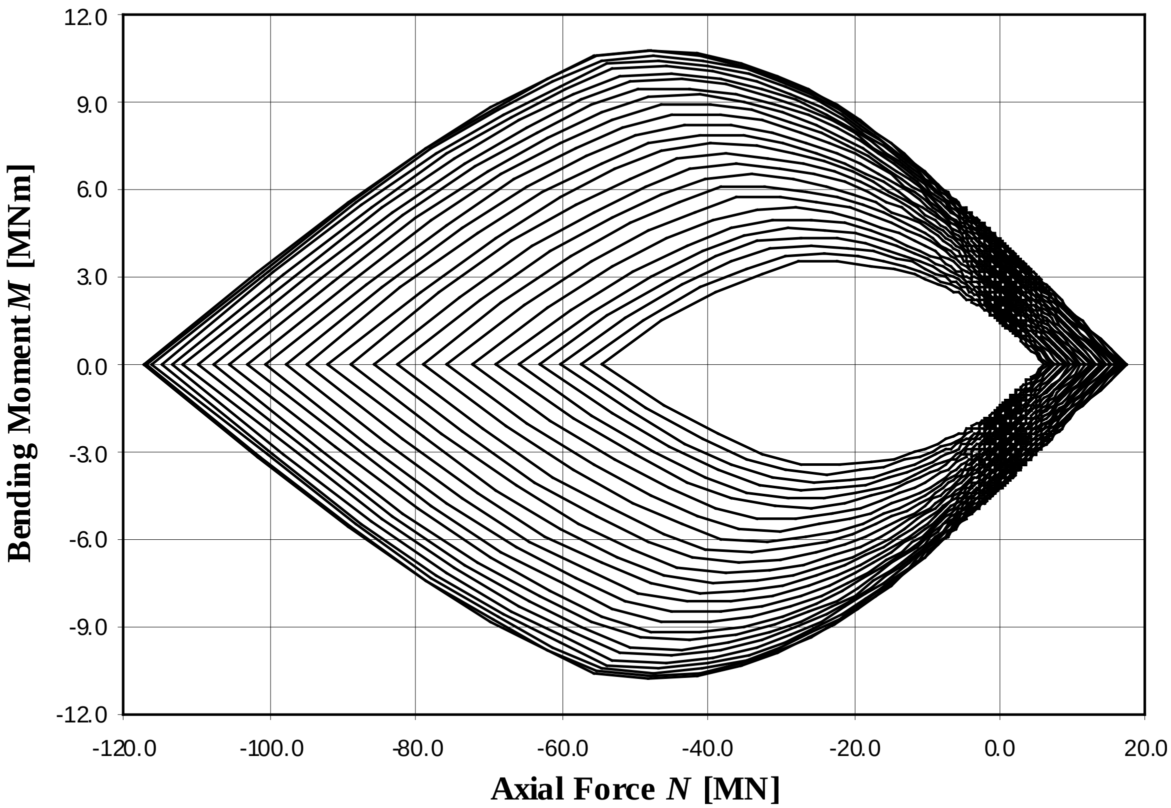
Time-variant Performance

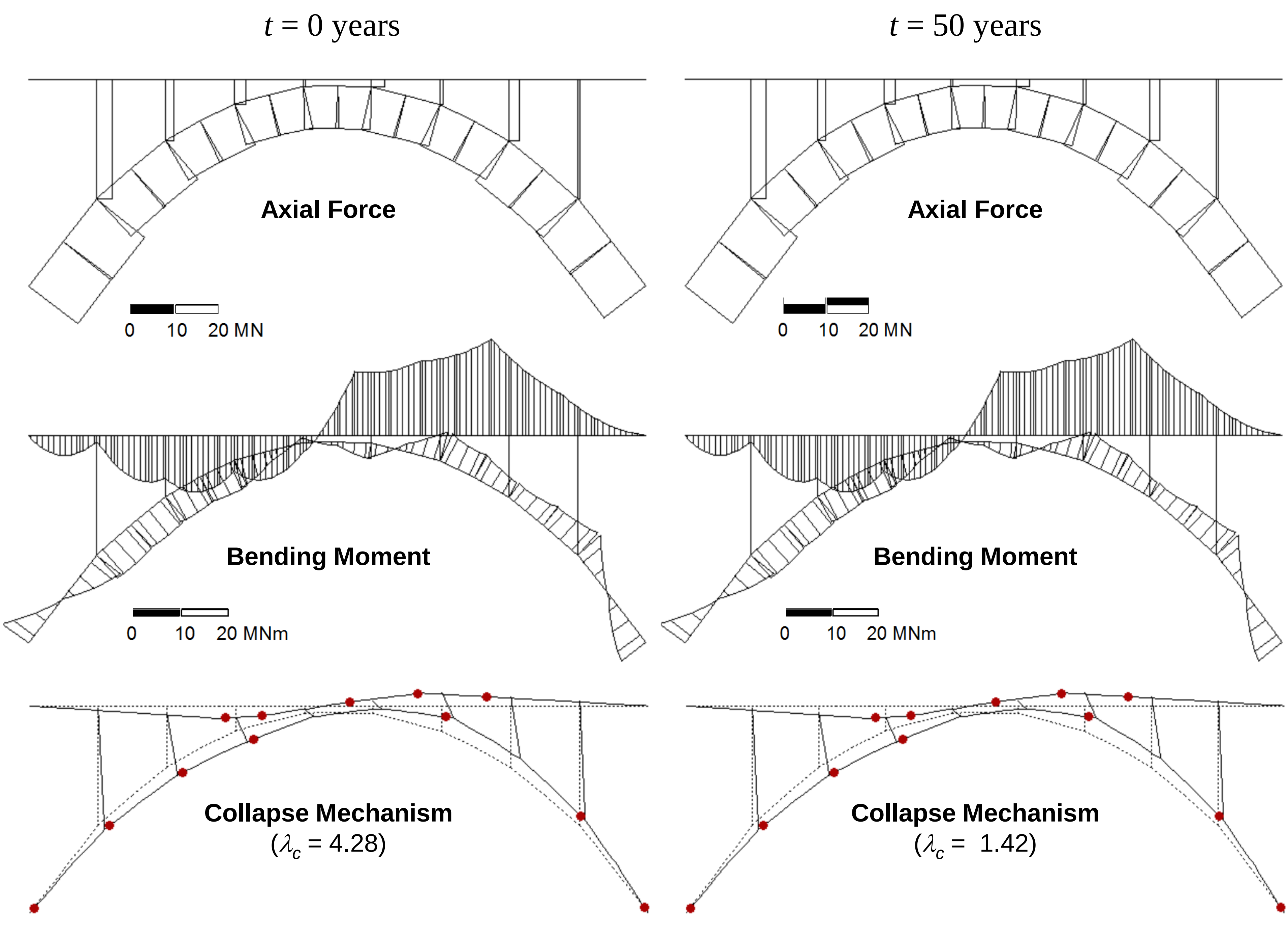




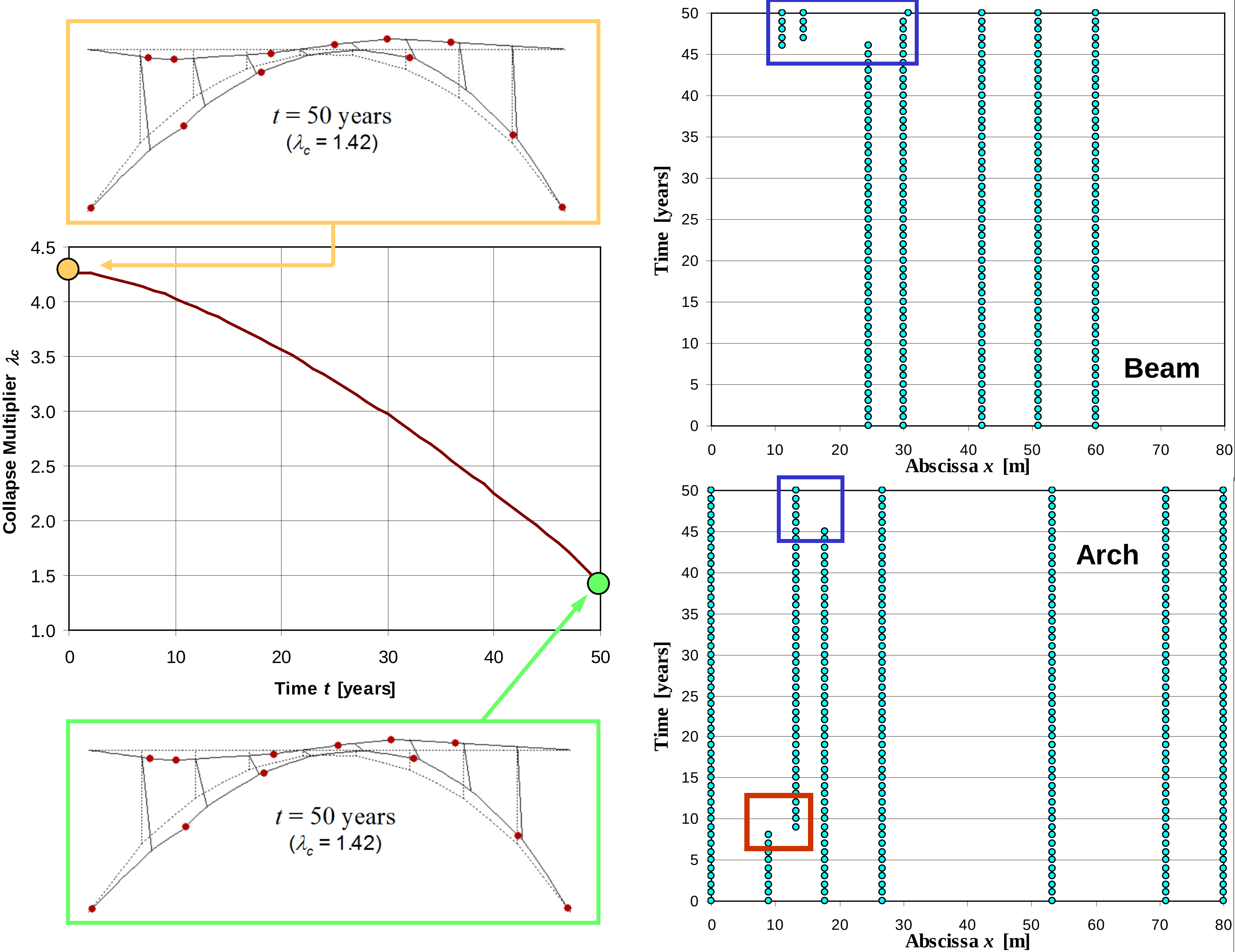
Time-variant Performance





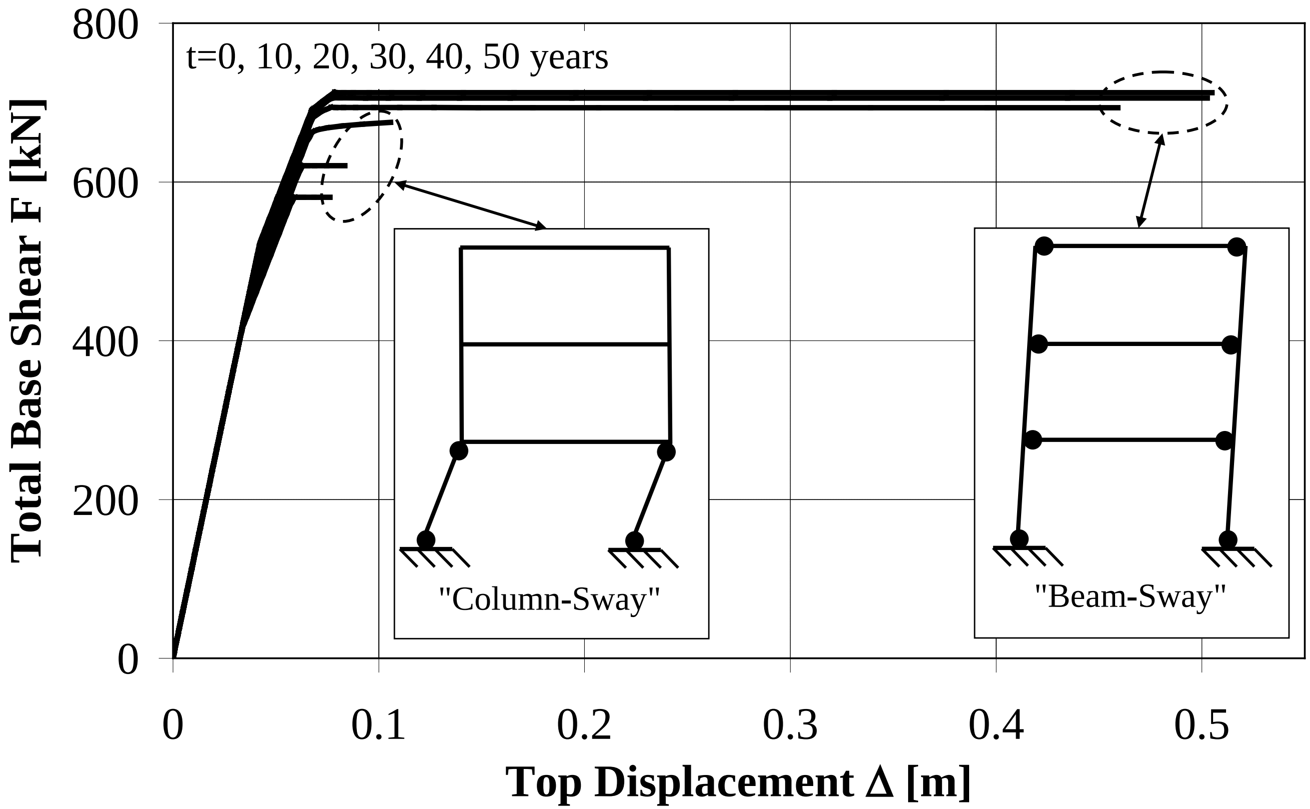


t = 0 years
t = 50 years
Axial Force
0 10 20 MN
Axial Force
0 10 20 MN
Bending Moment
0 10 20 MNm
Bending Moment
0 10 20 MNm
Collapse Mechanism
(λ_c = 4.28)
Collapse Mechanism
(λ_c = 1.42)



t = 50 years
(λc = 1.42)
Collapse Multiplier λc
Time t [years]
t = 50 years
(λc = 1.42)
Time [years]
Abscissa x [m]
Beam
Time [years]
Abscissa x [m]
Arch

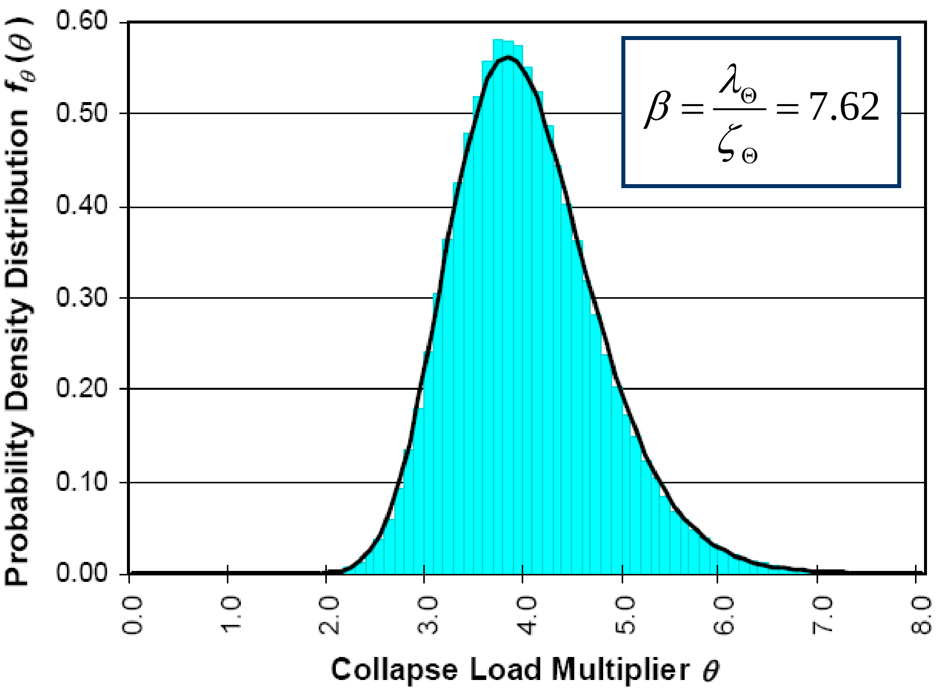
Seismic Capacity Design

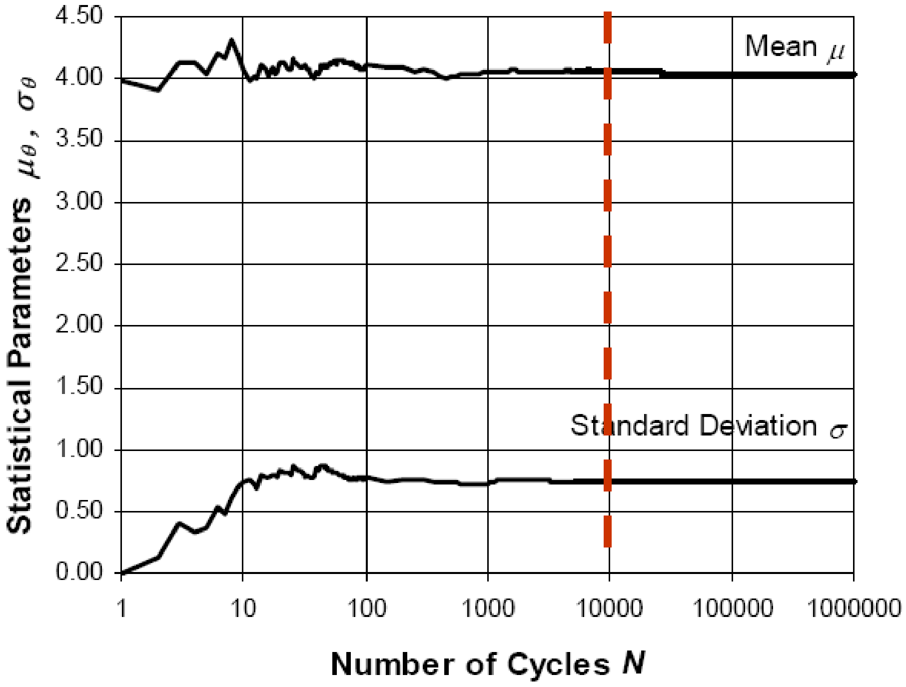


Biondini F., Palermo A., Toniolo G., 2011. Seismic Performance of Concrete Structures Exposed to Corrosion: Case Studies of Low-Rise Precast Buildings, *Structure and Infrastructure Engineering*, **7**(1-2).

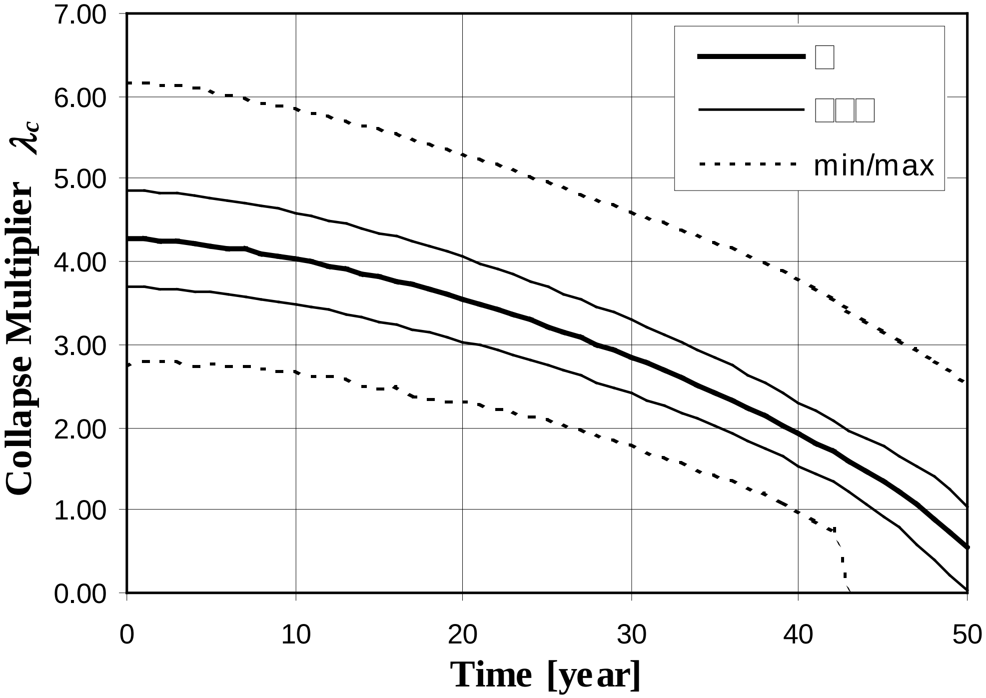
Probabilistic Analysis

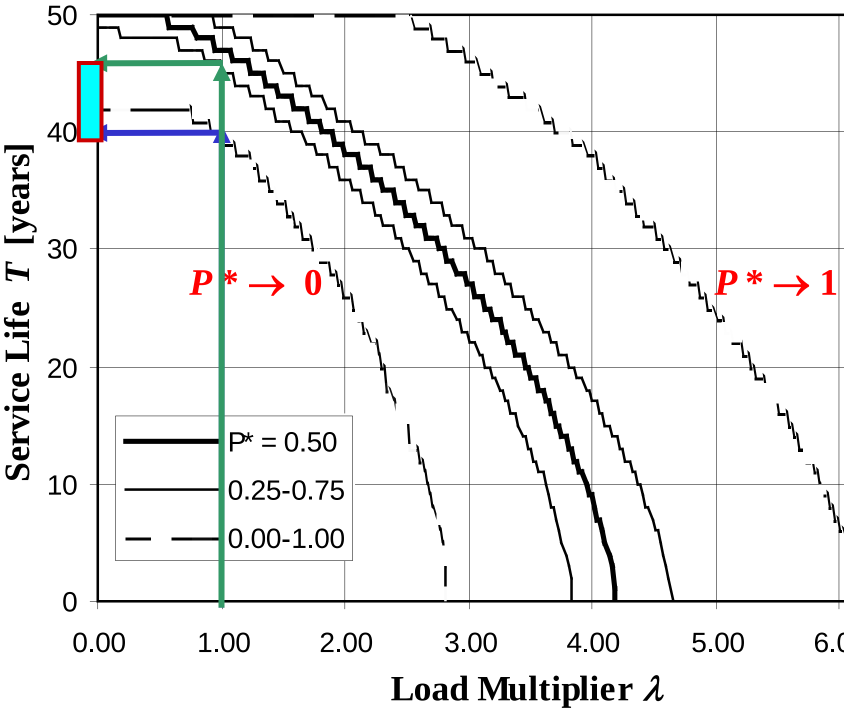
Variable	Distribution Type	μ	σ
$(\Delta x, \Delta y)$	Normal	0	50 mm
k	Lognormal	k_{nom}	$0.20\ k_{\text{nom}}$
g	Normal	g_{nom}	$0.10\ g_{\text{nom}}$
p	Normal	p_{nom}	$0.40\ p_{\text{nom}}$



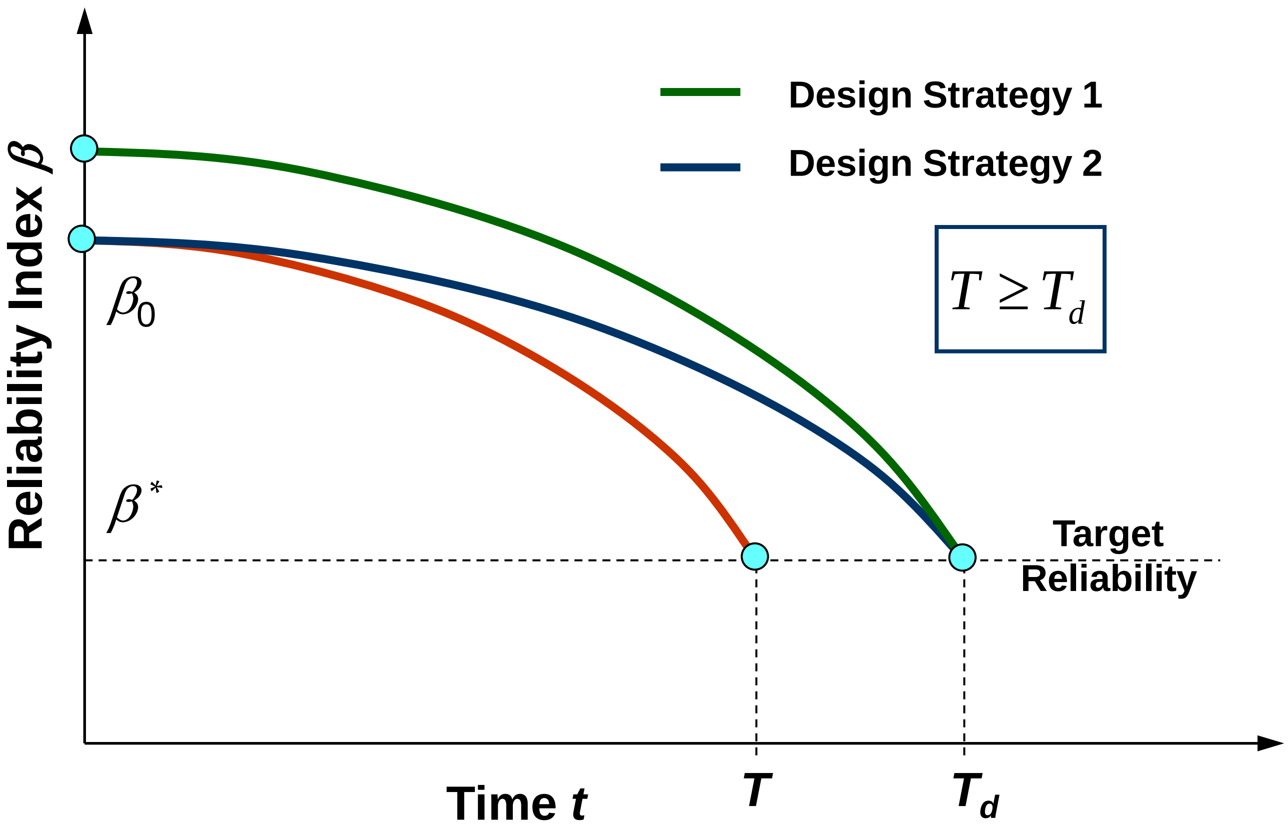


Probabilistic Lifetime Assessment





Design Lifetime



Arch Bridge

Bridge over the Breggia river (Cernobbio, Italy)

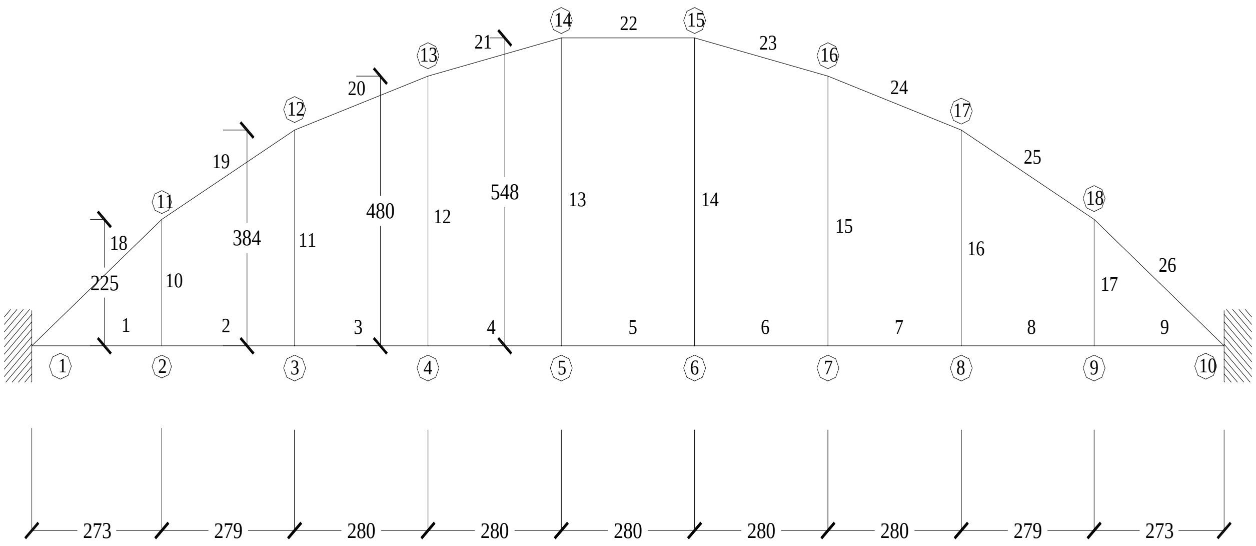
Damage State

- **Concrete Spalling**

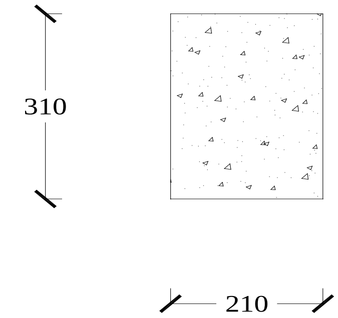
- **Steel Corrosion**

- **Deck Deterioration**

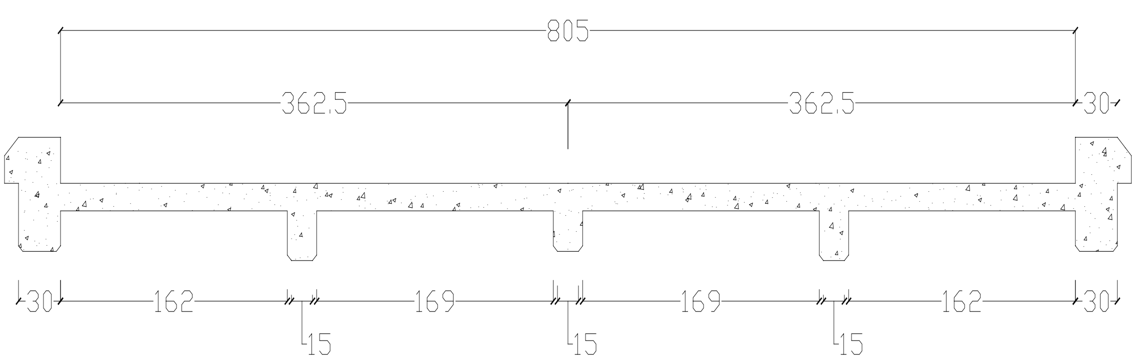
Structural Model



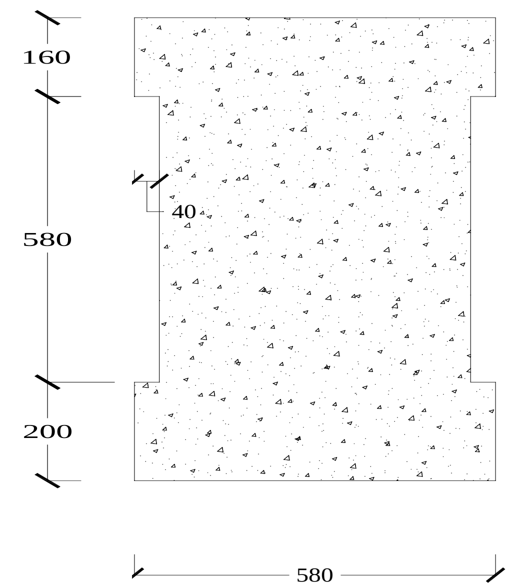
Bridge



Ties

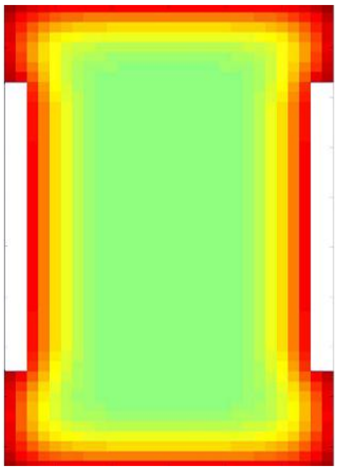


Deck

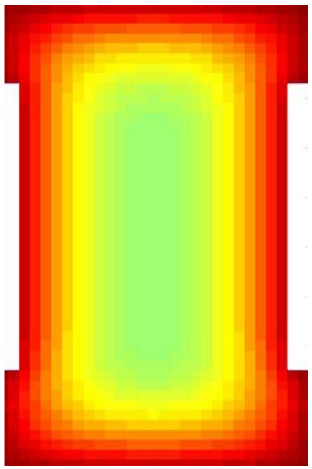


Arches

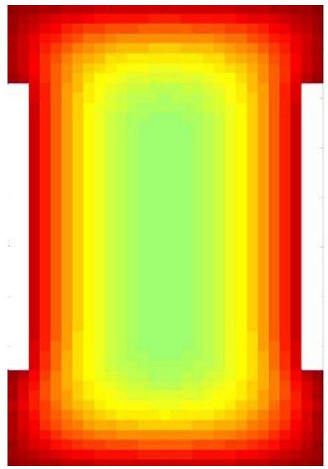
Concentration Maps : Arches



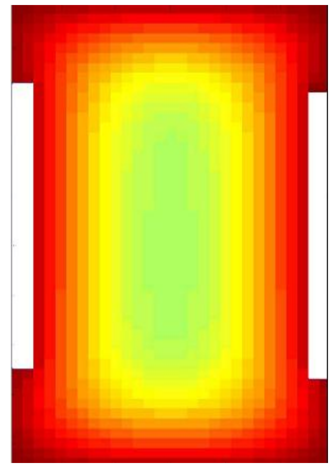
12 years



25 years



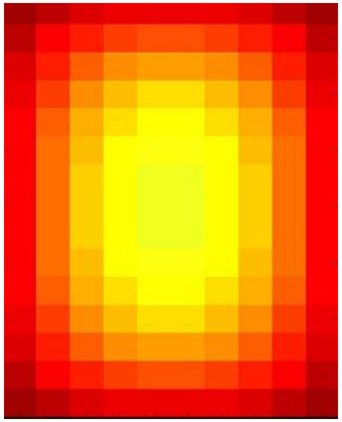
37 years



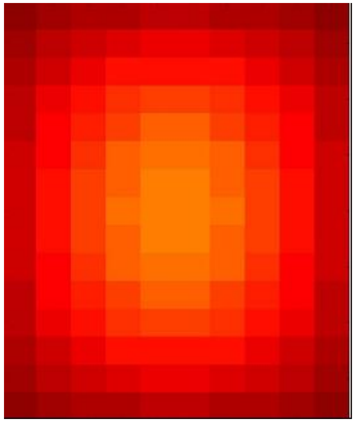
50 years

Actual State

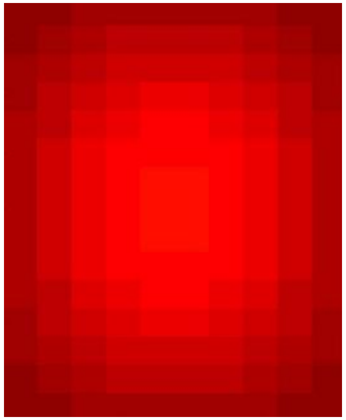
Concentration Maps: Ties



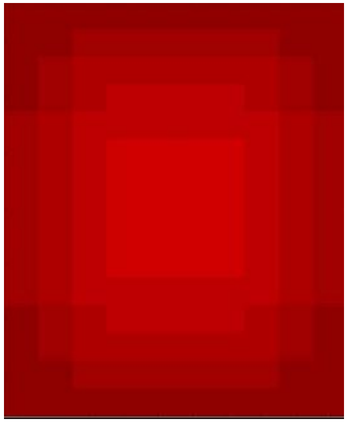
12 years



25 years



37 years

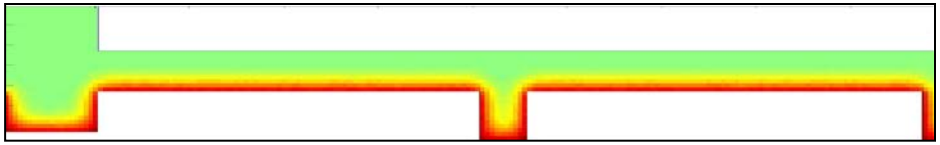


50 years

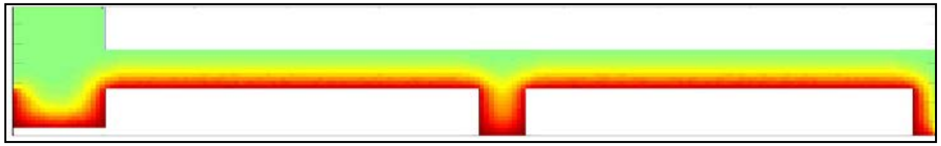
Actual State

Concentration Maps: Deck

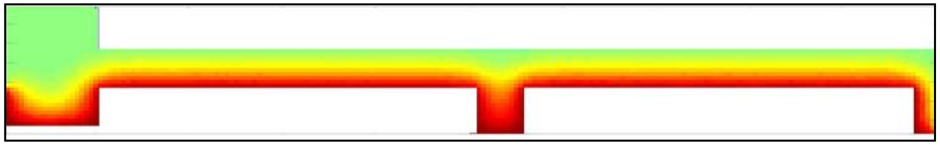
Aggressive Agent under the Deck



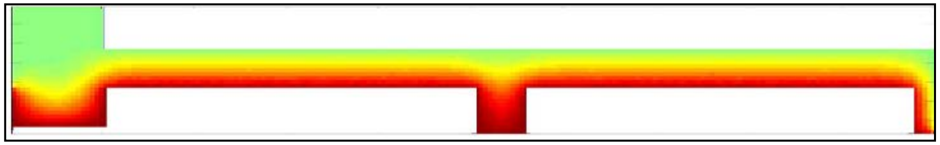
12 years



25 years



37 years

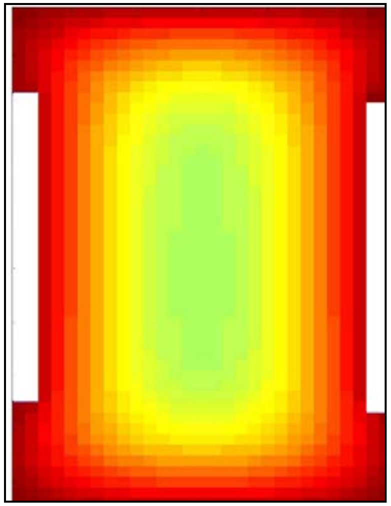


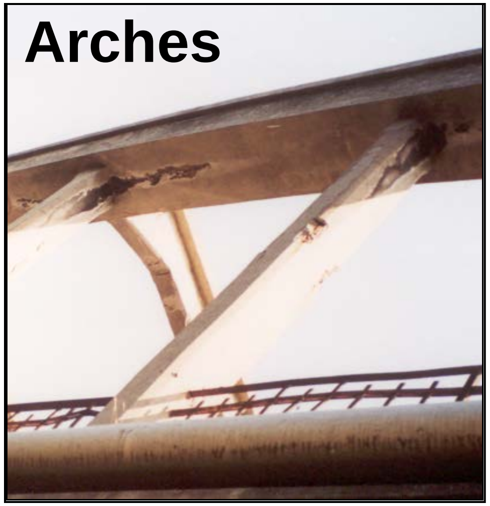
50 years

Actual State

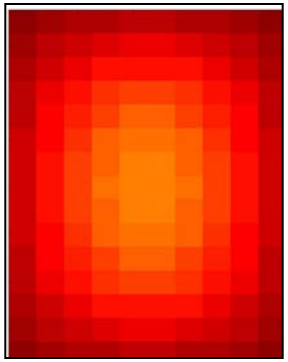
Diffusion vs Damage

Arches

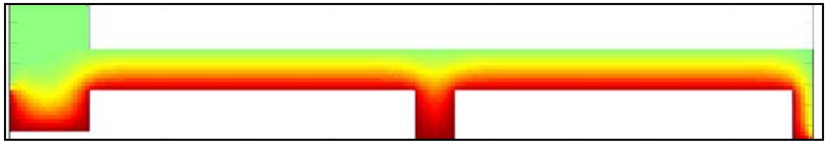




Ties

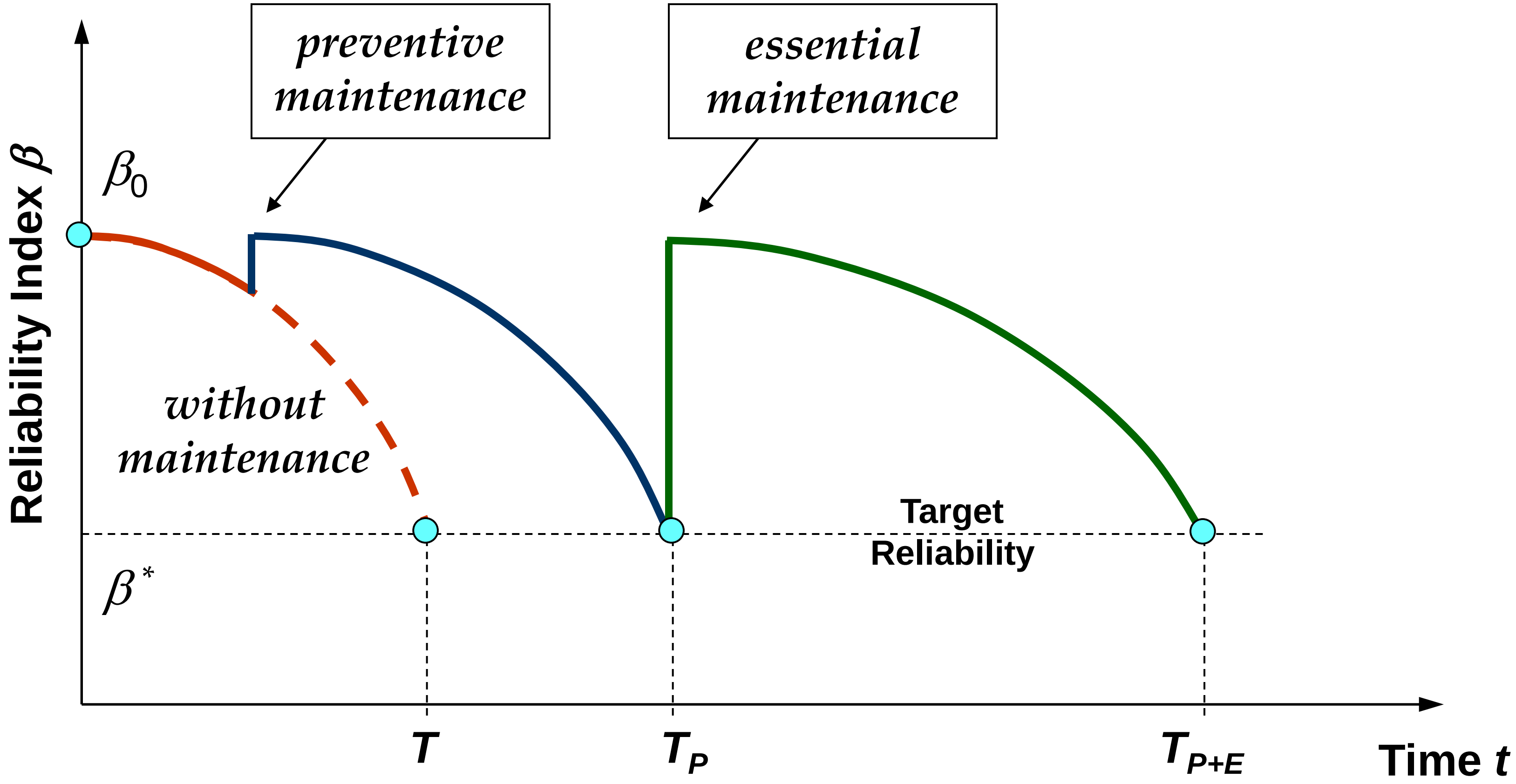


Deck

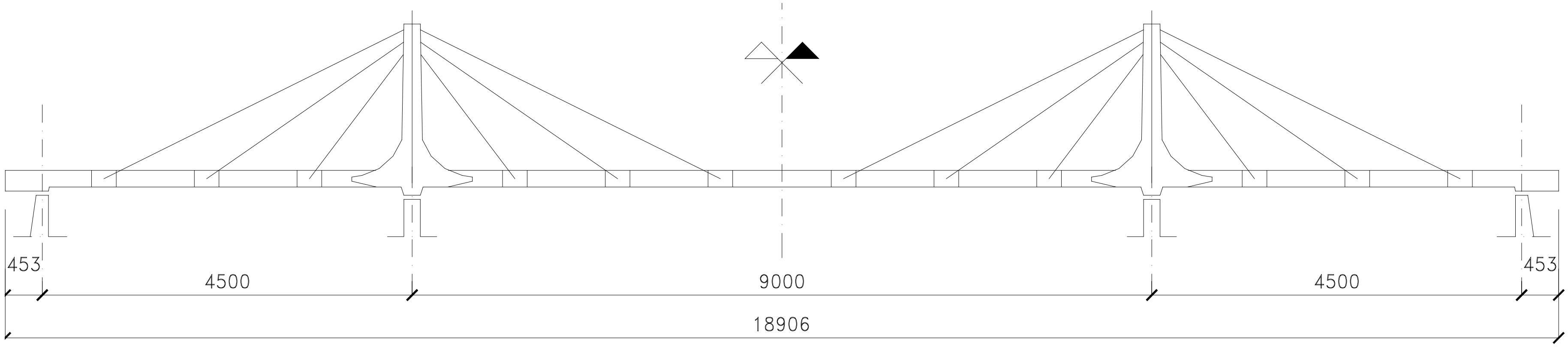


Repair Intervention

Role of Maintenance

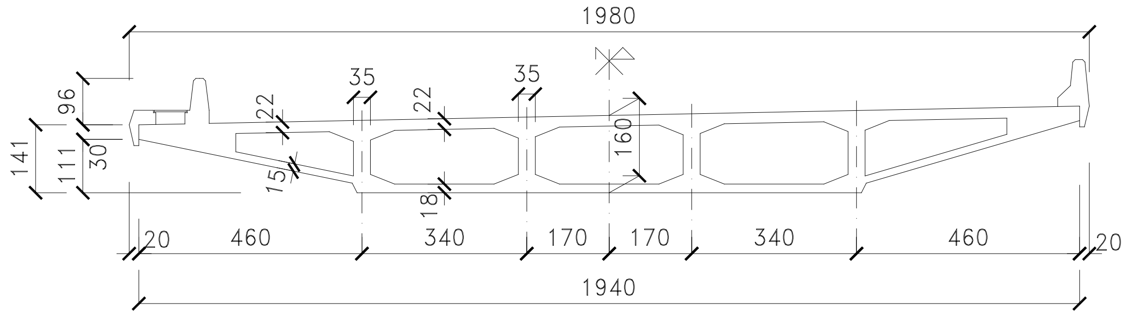


Certosa Cable-Stayed Bridge

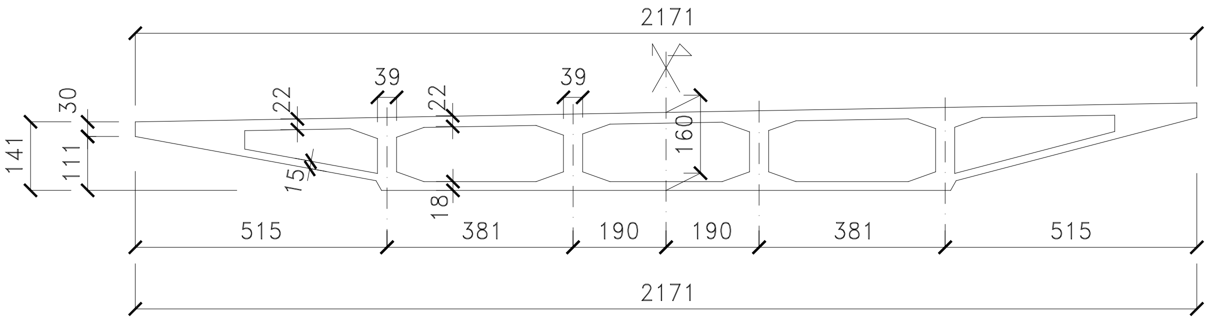


Biondini, F., Frangopol, D.M. & Malerba, P.G. 2006b. Time-variant Performance of the Certosa Cable-stayed Bridge. *Structural Engineering International*, IABSE, **16**(3), 2006, 235-244

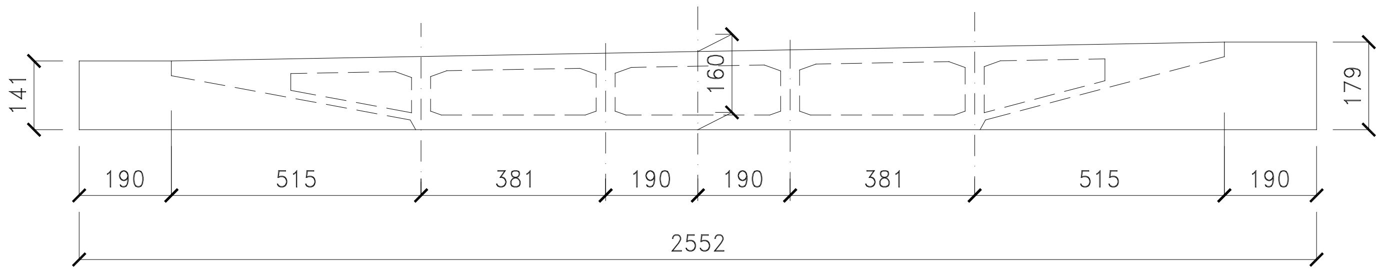
Deck Cross-sections



Straight cross-section.

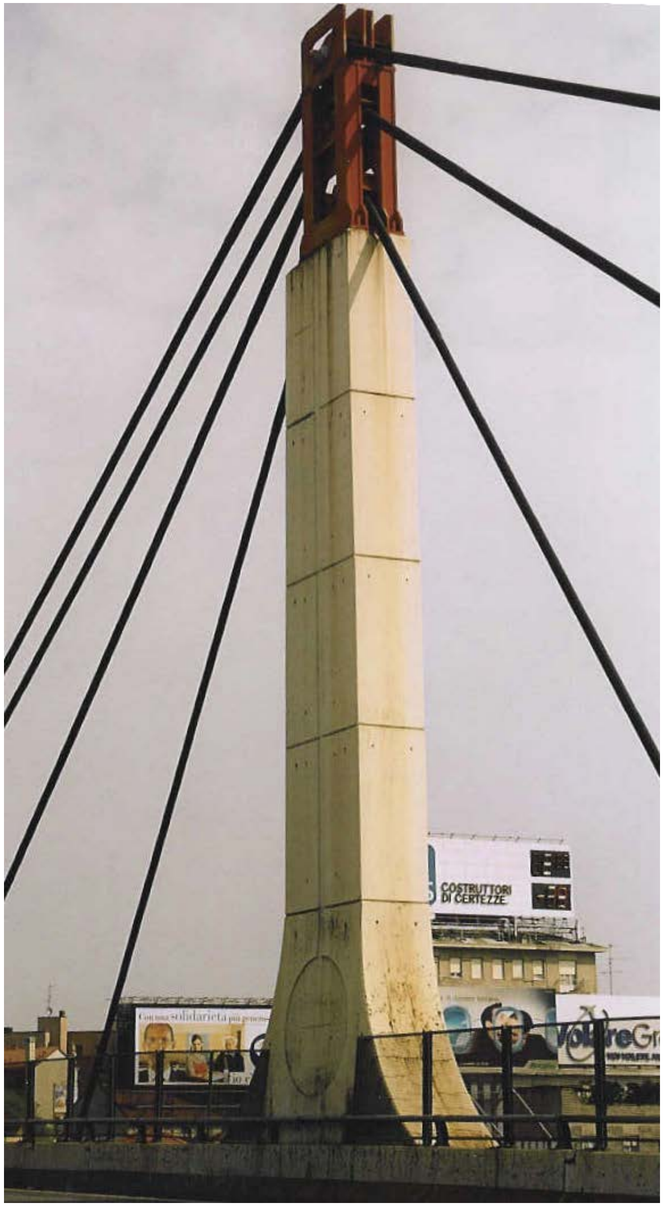


Skewed cross-section.



Skewed cross-section on the transversal beam.

Pylons



Repair Interventions

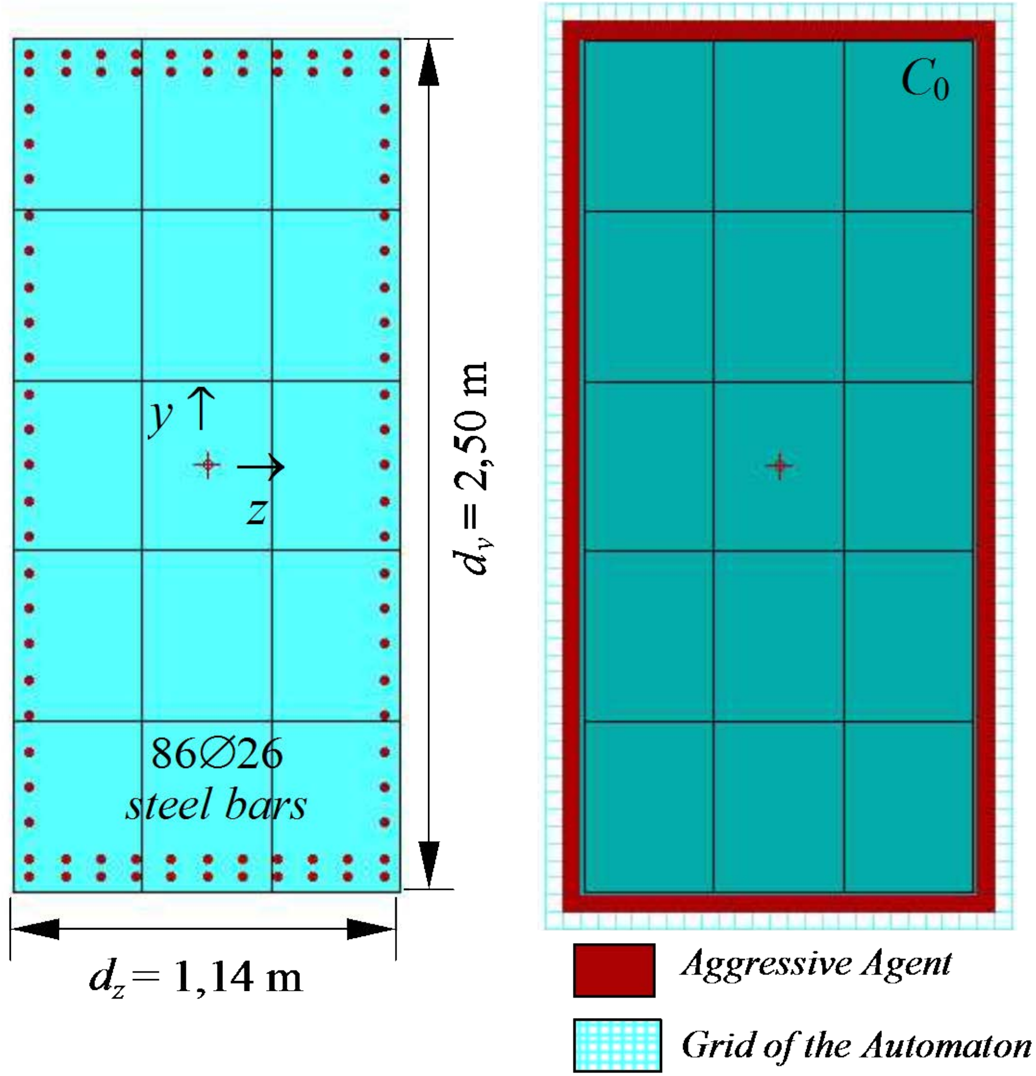
➢ The concrete cover has been restored by a multilayered repair in order to protect the structure from future diffusive attacks of external aggressive agents.

(1) Sandblasting.

(2) Local sutures with tixotropic, anti-shrinkage, polypropylene fiber reinforced mortar.

(3) Skin protection with high adhesion and high elasticity sealing cement mortar, reinforced with double or simple skin mesh.

Structural Model and Exposure Scenario

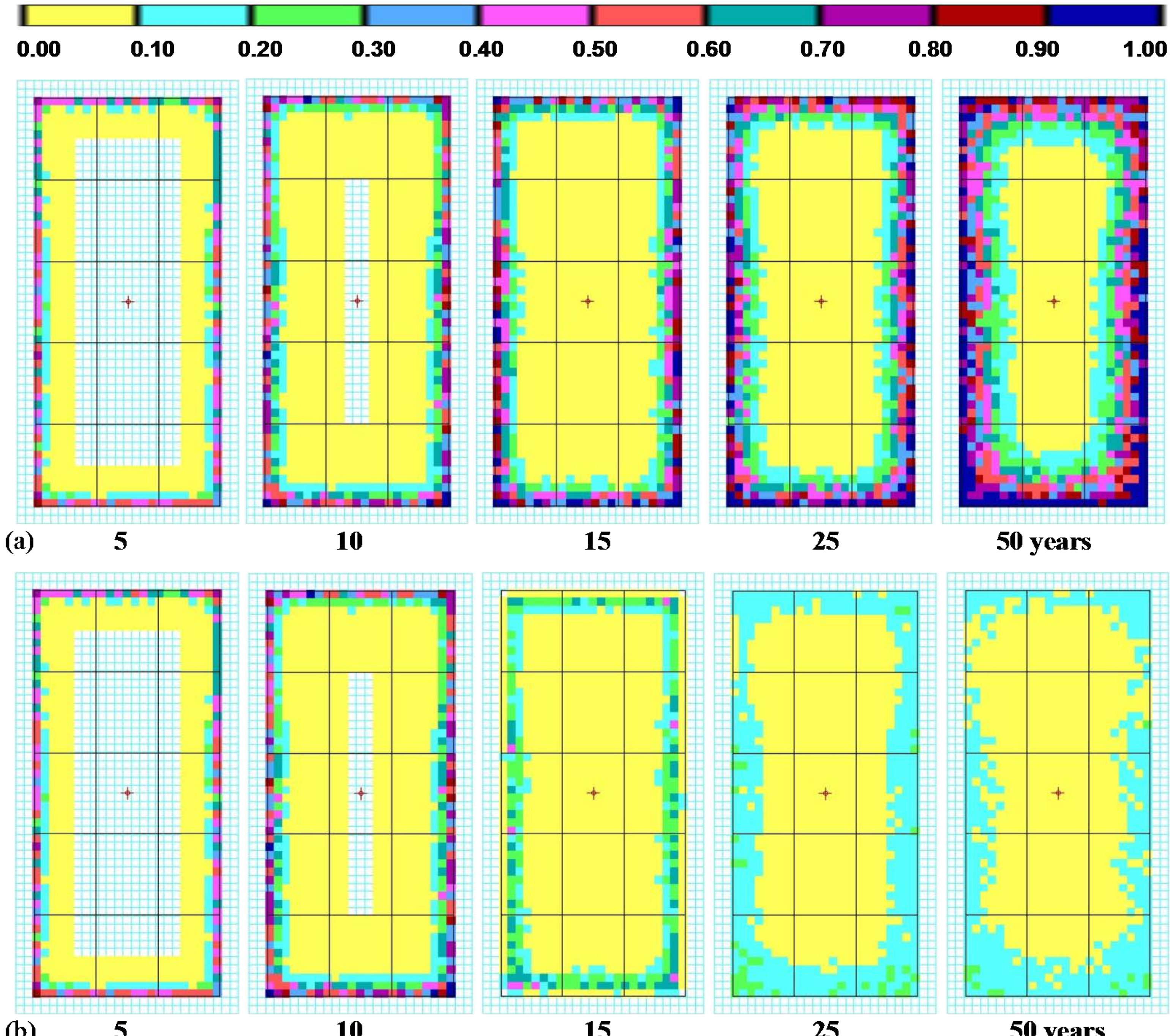


Concentration Maps

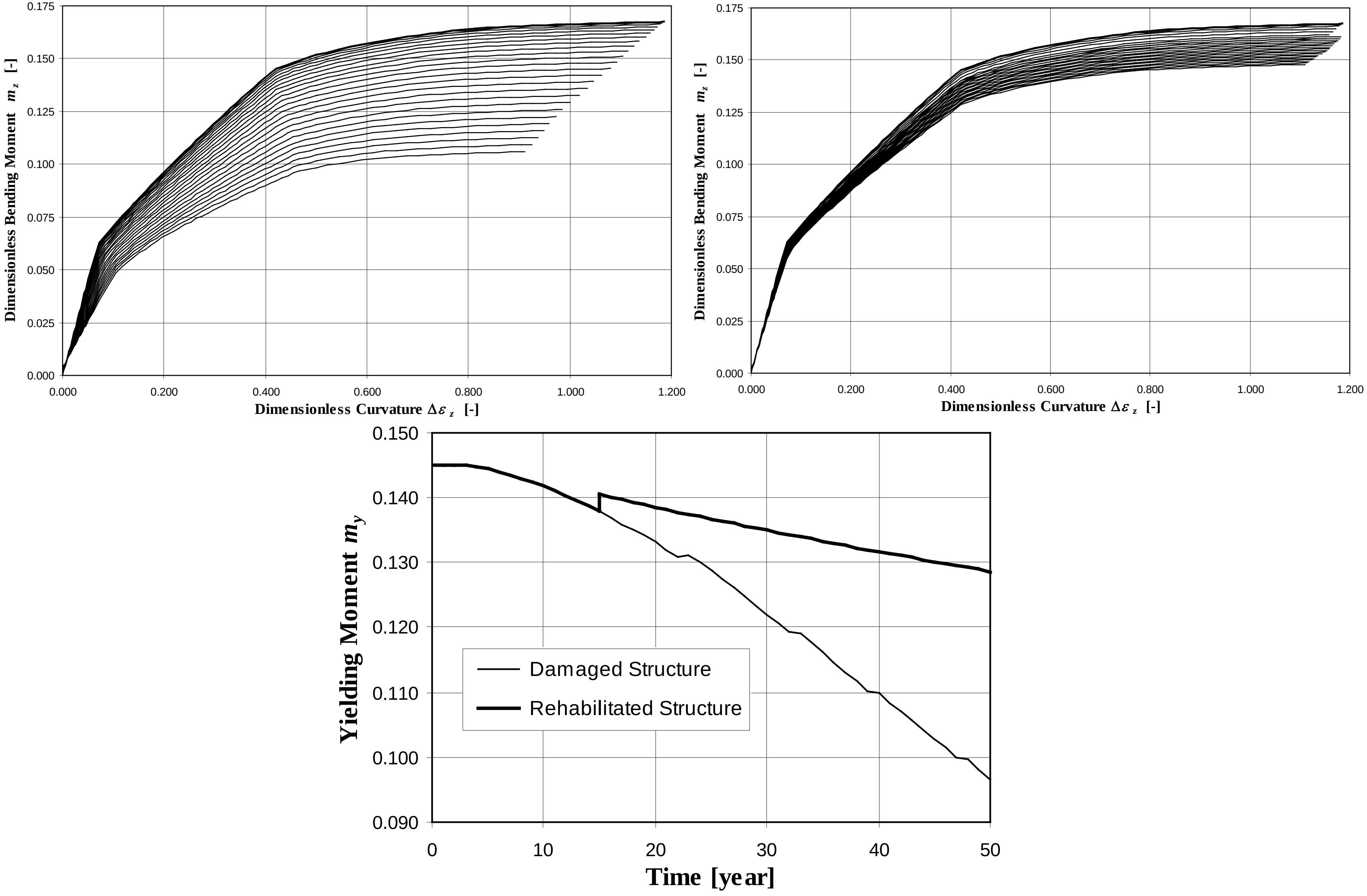
$C(x,t)/C_0$

(a) Damaged Structure

(b) Rehabilitated Structure



Time-variant Performance

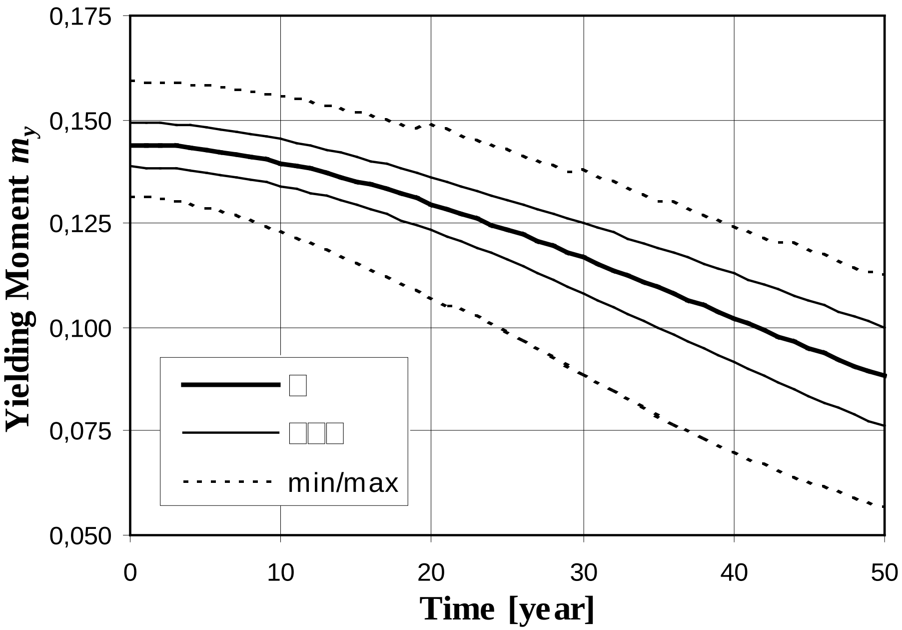


Probabilistic Model

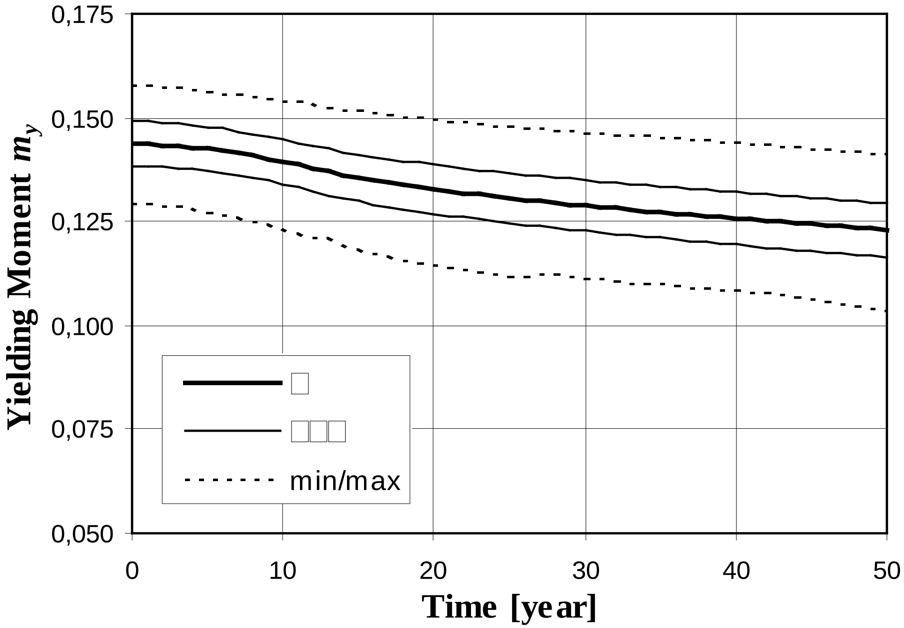
Random Variable ($t=t_0$)	Type	μ	σ
Concrete strength f_c	Lognormal	$f_{c,nom}$	5 MPa
Steel strength f_{sy}	Lognormal	$f_{sy,nom}$	30 MPa
Coordinates of the nodal points (y_i, z_i)	Normal	$(y_i, z_i)_{nom}$	5 mm
Coordinates of the steel bars (y_m, z_m)	Normal	$(y_m, z_m)_{nom}$	5 mm
Diameter of the steel bars $\varnothing_m$	Normal	$\varnothing_{m,nom}$	$0.10\varnothing_{m,nom}$
Diffusivity coefficient D	Normal	D_{nom}	$0.10\ D_{nom}$
Concrete damage rate q_c	Normal	$q_{c,nom}$	$0.30\ q_{c,nom}$
Steel damage rate q_s	Normal	$q_{s,nom}$	$0.30\ q_{s,nom}$

Probabilistic Time-variant Performance

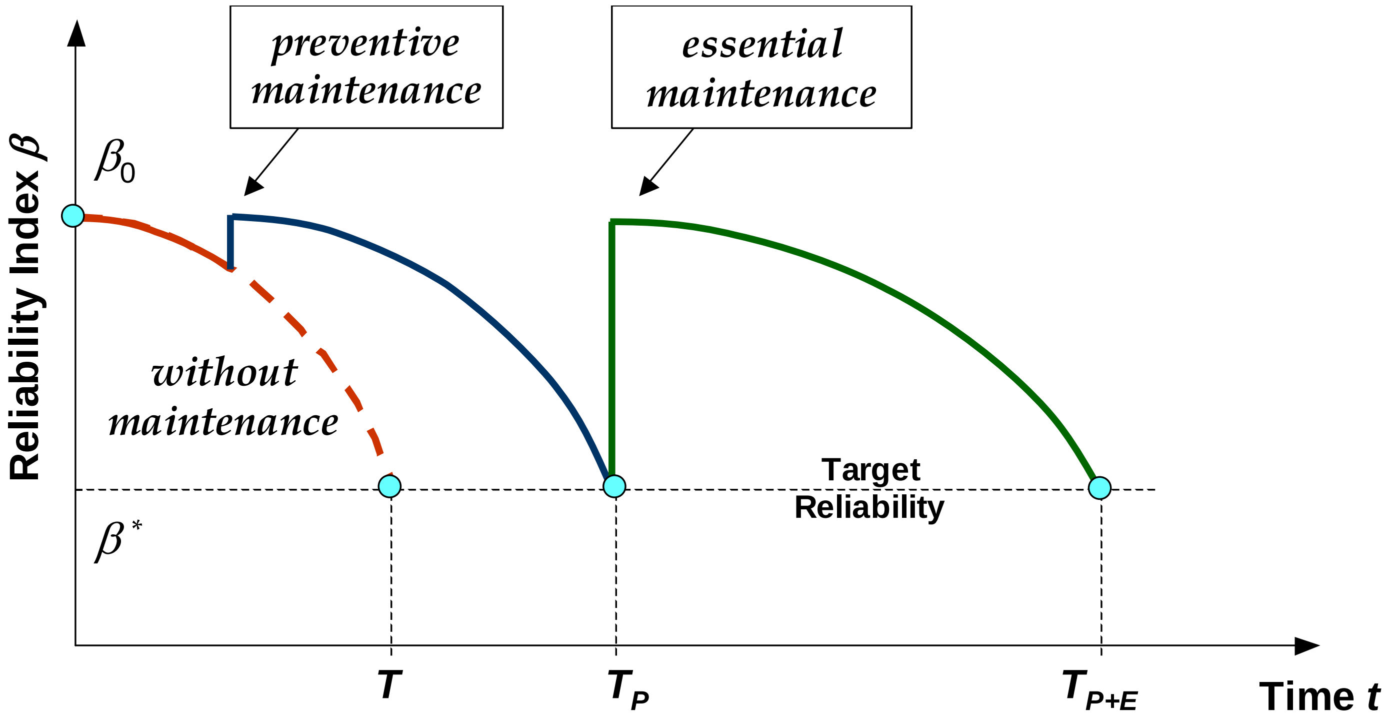
Damaged Structure



Rehabilitated Structure



Maintenance Costs

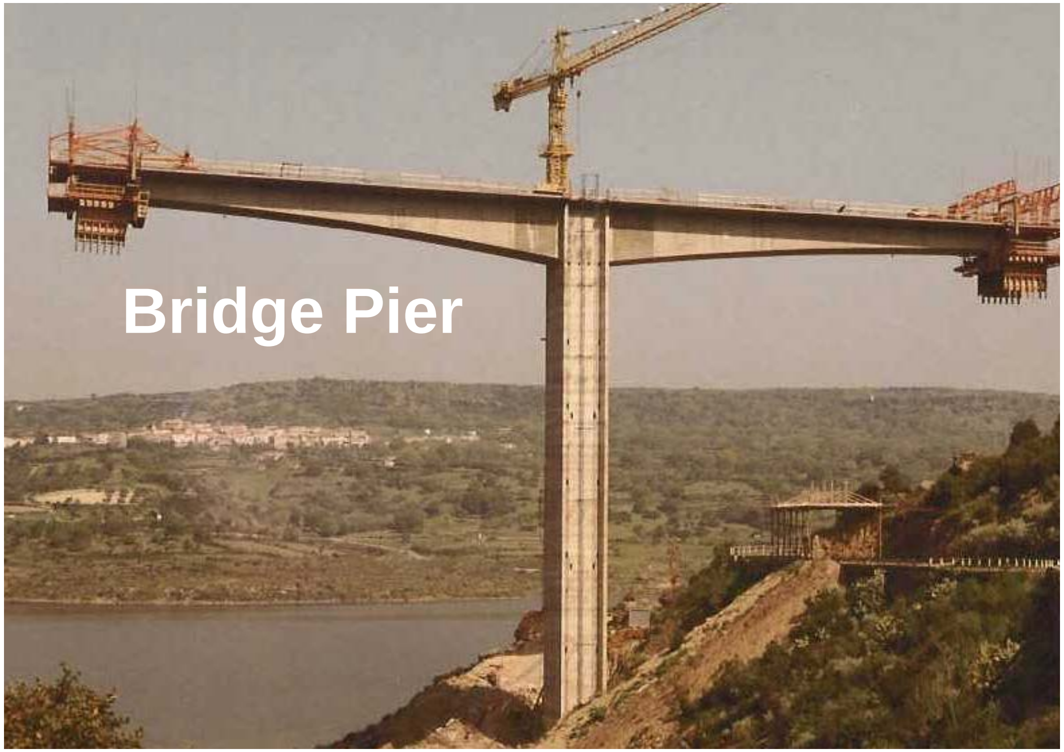


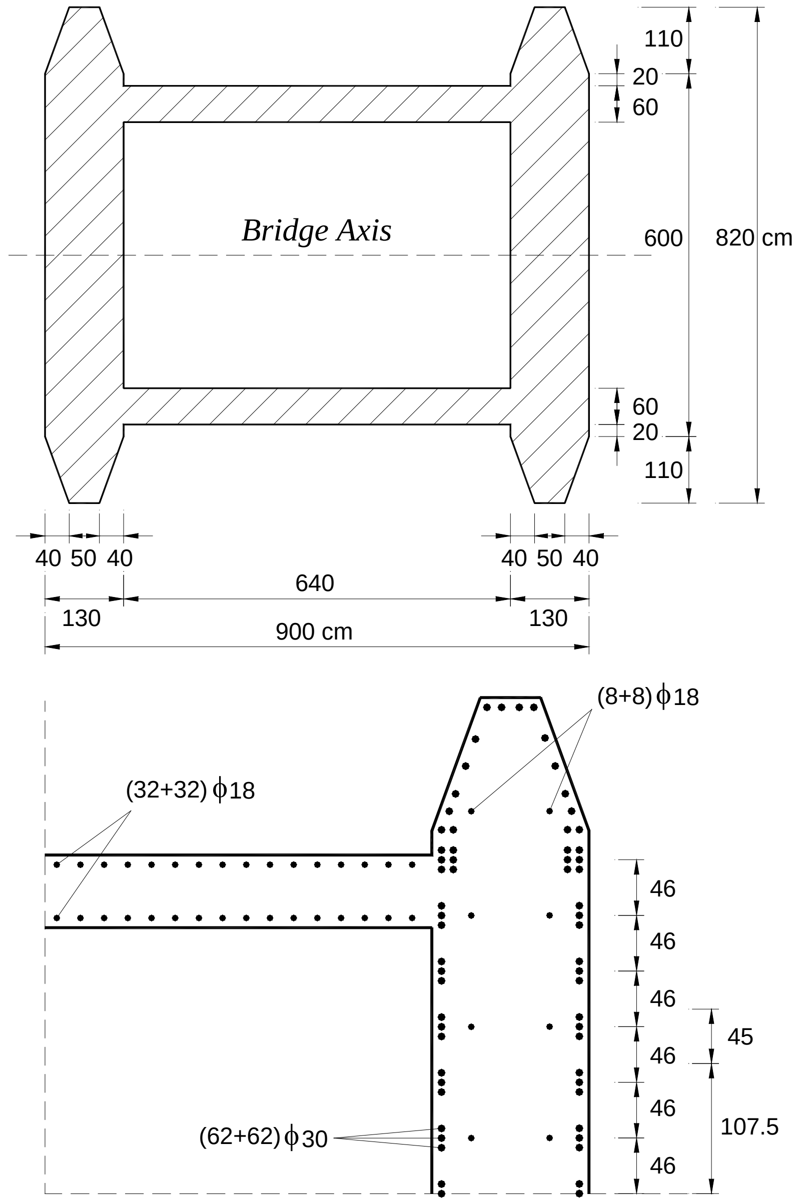
$$\beta(t) = \beta_0(t) + \sum_{i=1}^{n} \Delta\beta_i(t)$$

$$C_i = \alpha\, \Delta\beta_i$$

$$C = \sum_{i=1}^{n} \frac{C_i}{(1+v)^{t_i}} = \sum_{i=1}^{n} C_{0i}$$

- $\Delta\beta_i$ = modification of the reliability index associated with the intervention i=1,…n applied at time t_i
- C_i = Cost of the intervention i at time t_i
- C_{0i} = Cost C_i referred to the initial time t_0
- v = Discount rate

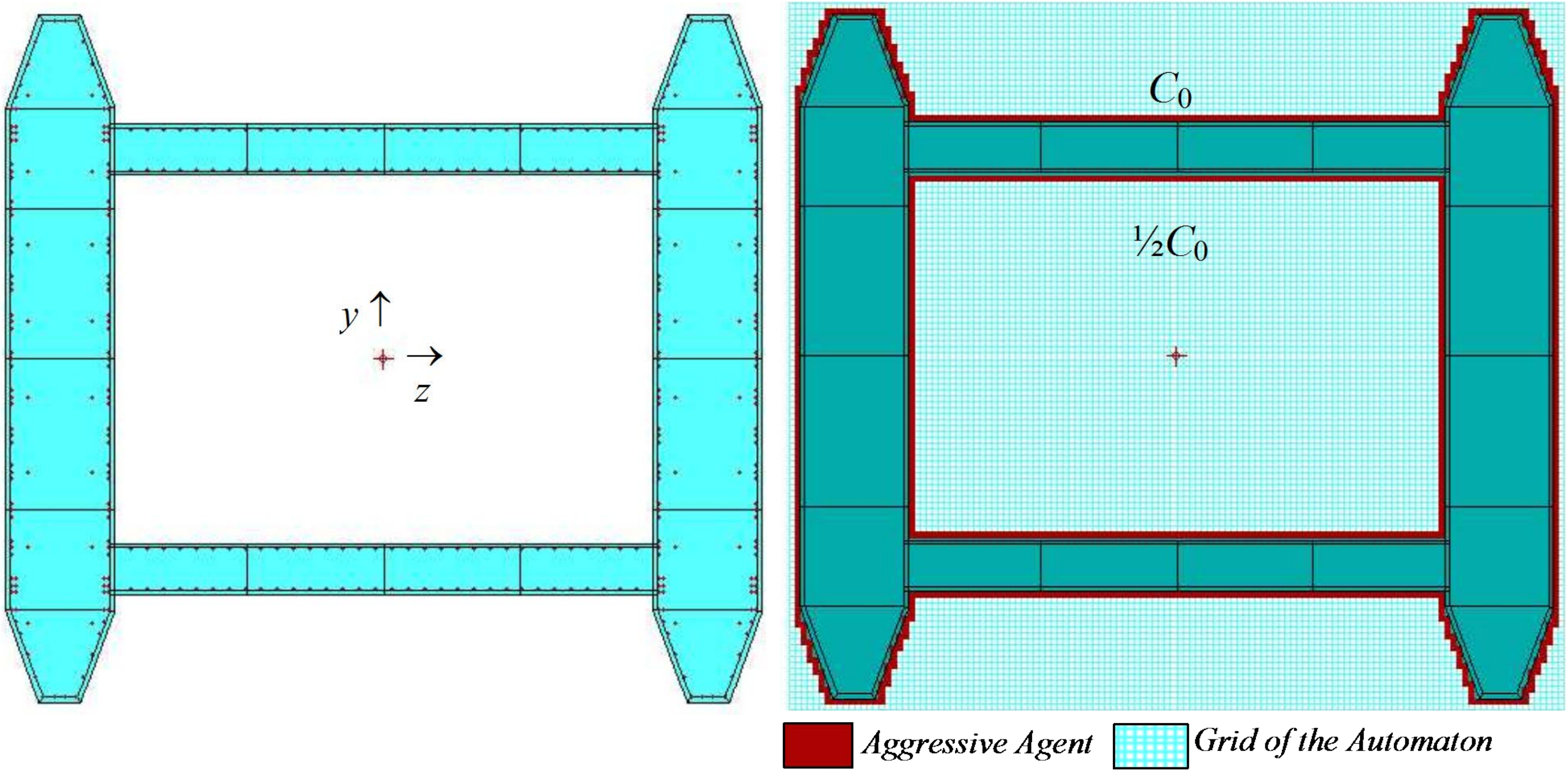




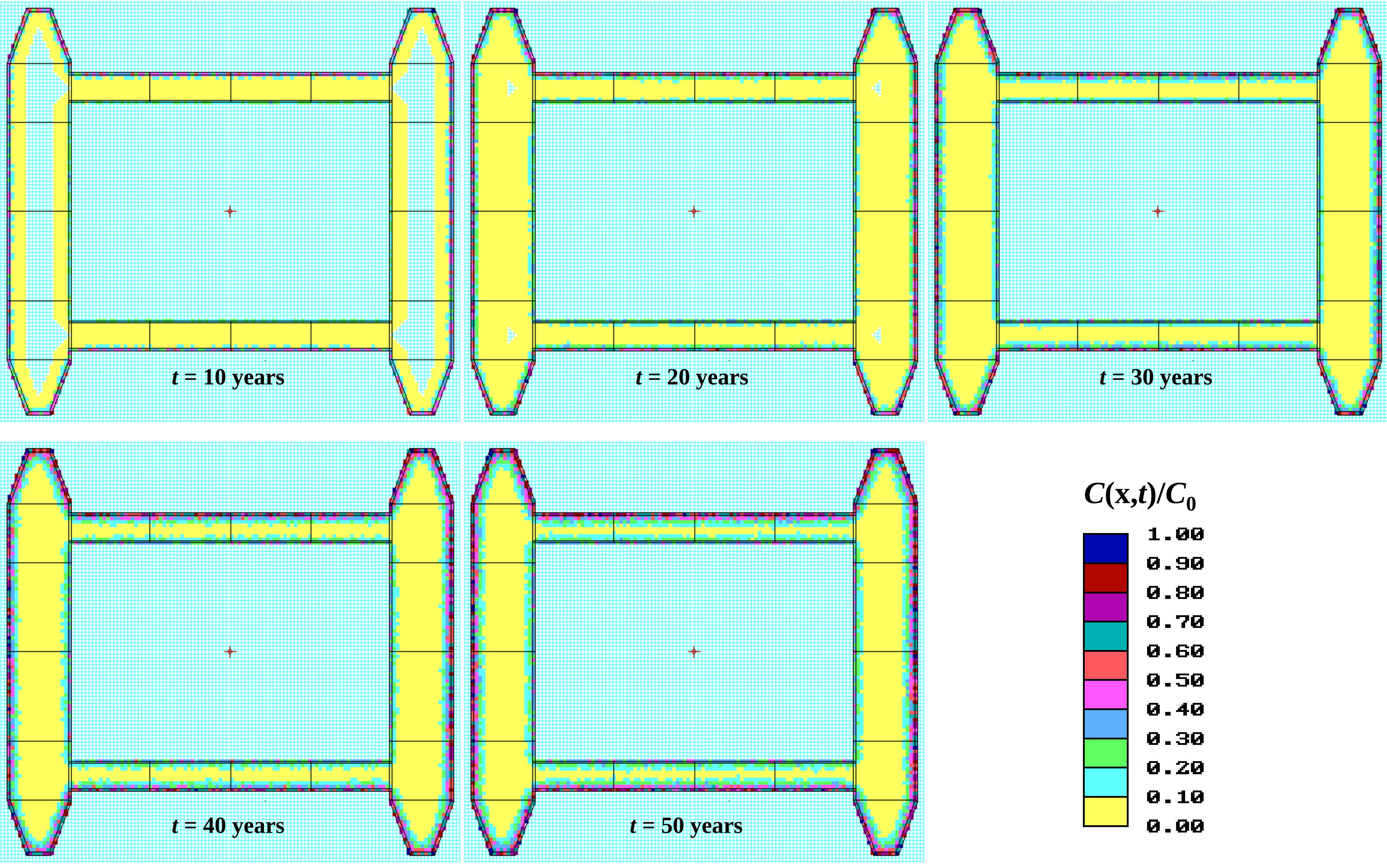
Biondini, F., Bontempi, F., Frangopol, D.M. & Malerba, P.G. 2006. Probabilistic Service Life Assessment and Maintenance Planning of Concrete Structures, *Journal of Structural Engineering*, ASCE, **132**(5).

Bridge Pier Reinforced with a Total of
$160\,\phi 18 + 248\,\phi 30 = 408$ *Steel Bars*

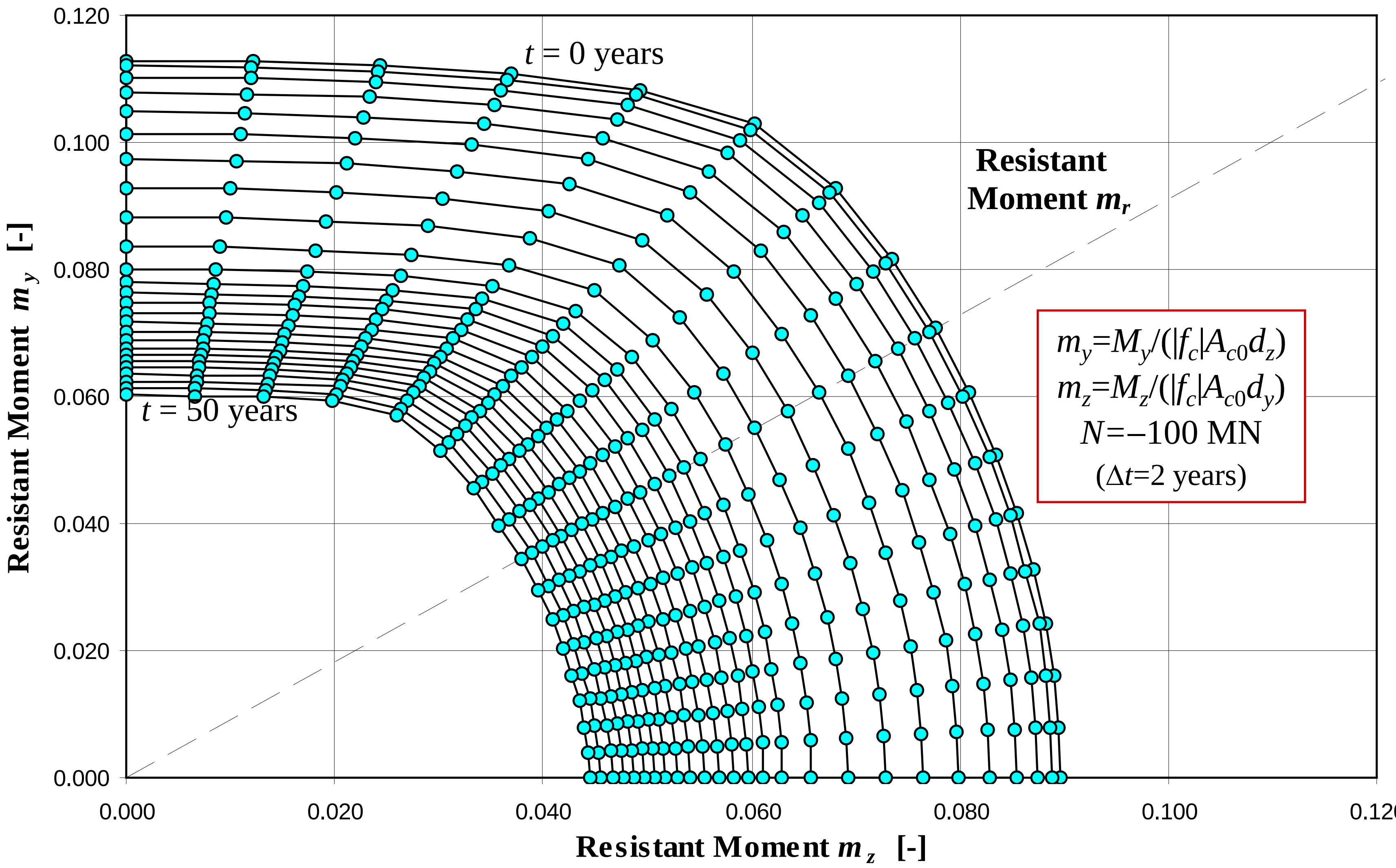
Structural Model and Exposure Scenario



Concentration Maps

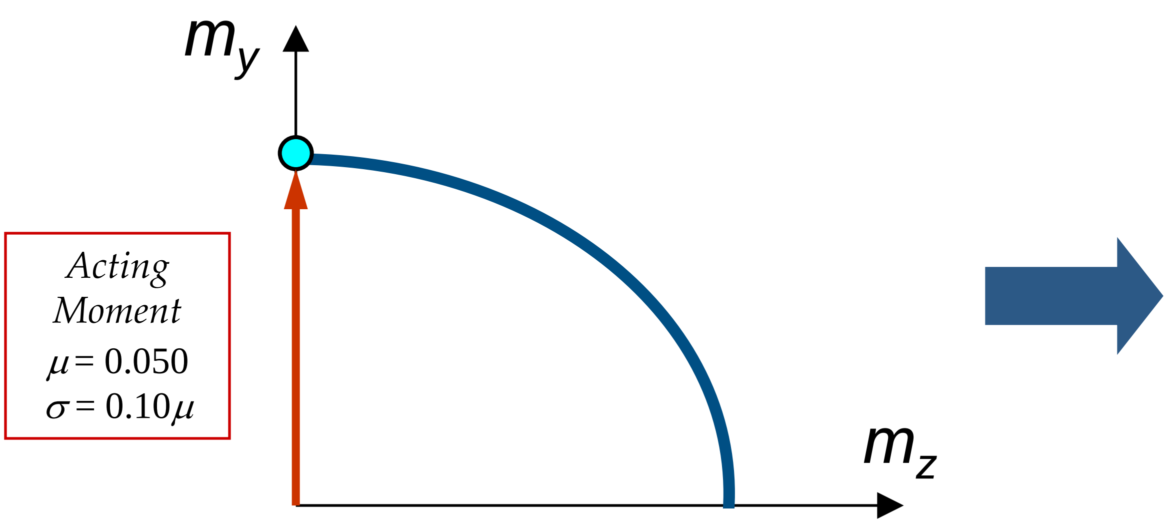


Resistance Domains M_y-M_z



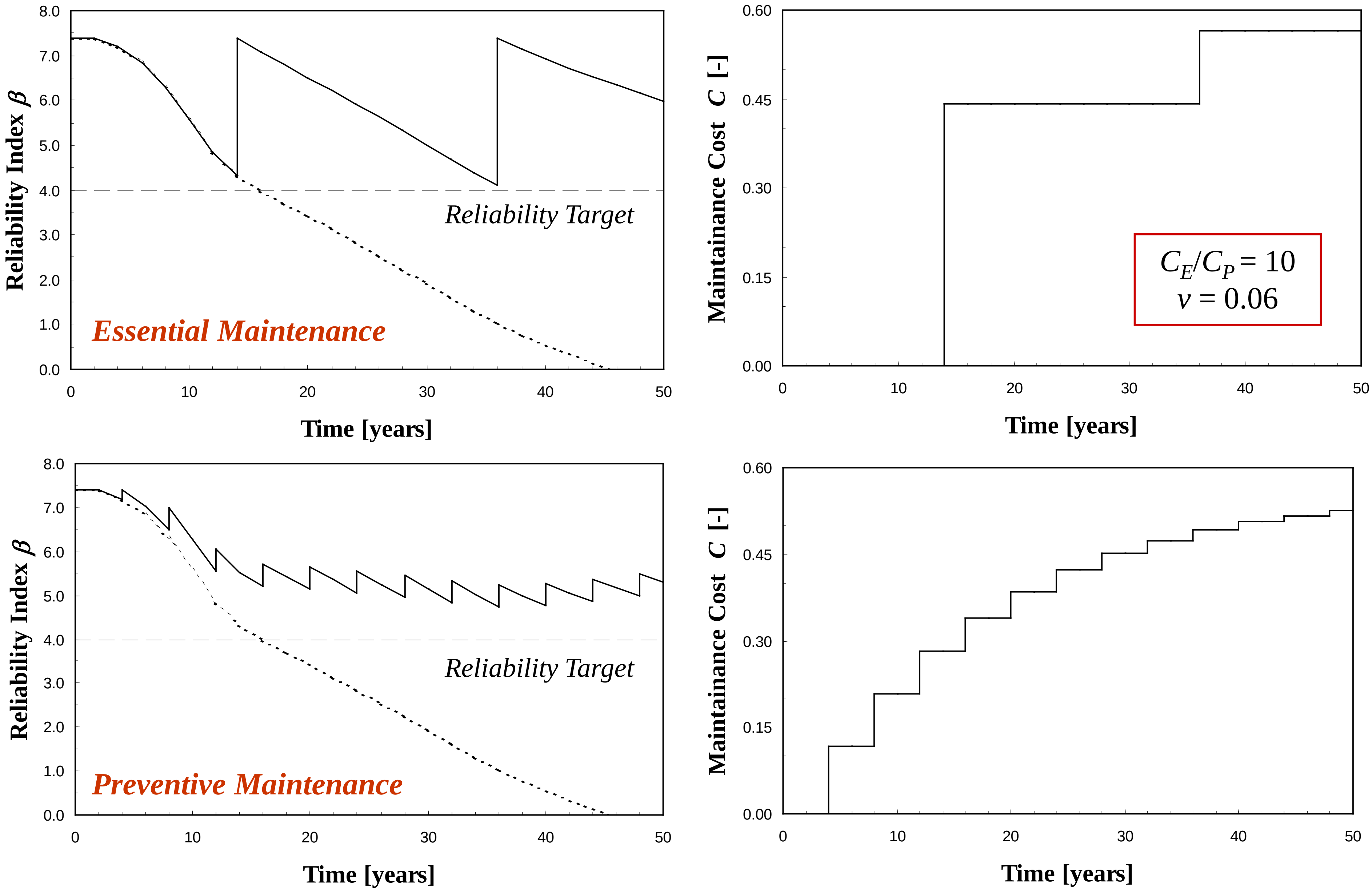
Probabilistic Model

Random Variable ($t=t_0$)	Type	μ	σ
Concrete strength f_c	Lognormal	$f_{c,nom}$	5 MPa
Steel strength f_{sy}	Lognormal	$f_{sy,nom}$	30 MPa
Coordinates of the nodal points (y_i, z_i)	Normal	$(y_i, z_i)_{nom}$	5 mm
Coordinates of the steel bars (y_m, z_m)	Normal	$(y_m, z_m)_{nom}$	5 mm
Diameter of the steel bars $\varnothing_m$	Normal	$\varnothing_{m,nom}$	$0.10\varnothing_{m,nom}$
Diffusivity coefficient D	Normal	D_{nom}	$0.10\ D_{nom}$
Concrete damage rate q_c	Normal	$q_{c,nom}$	$0.30\ q_{c,nom}$
Steel damage rate q_s	Normal	$q_{s,nom}$	$0.30\ q_{s,nom}$



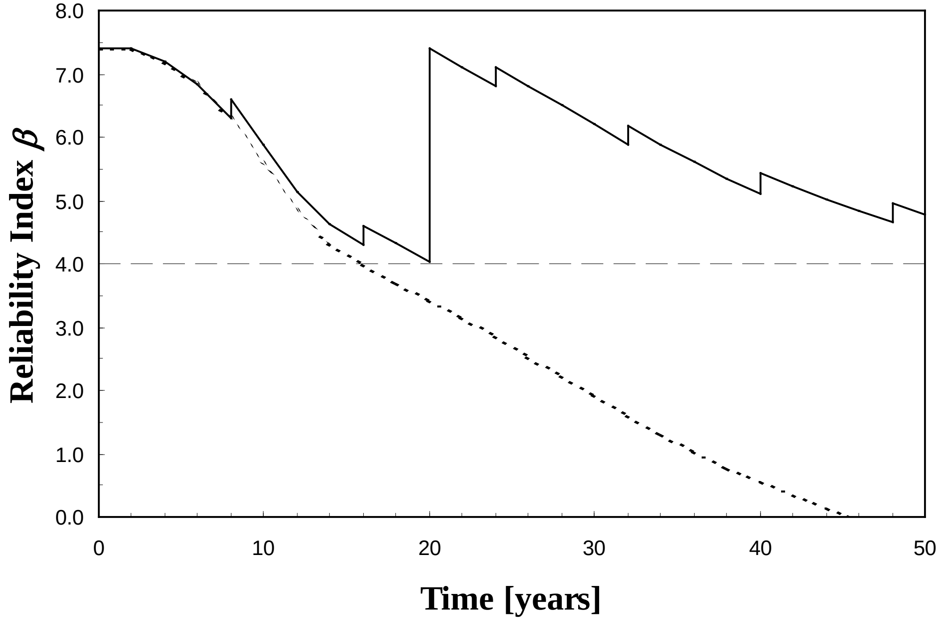
$\beta = \beta(t)$

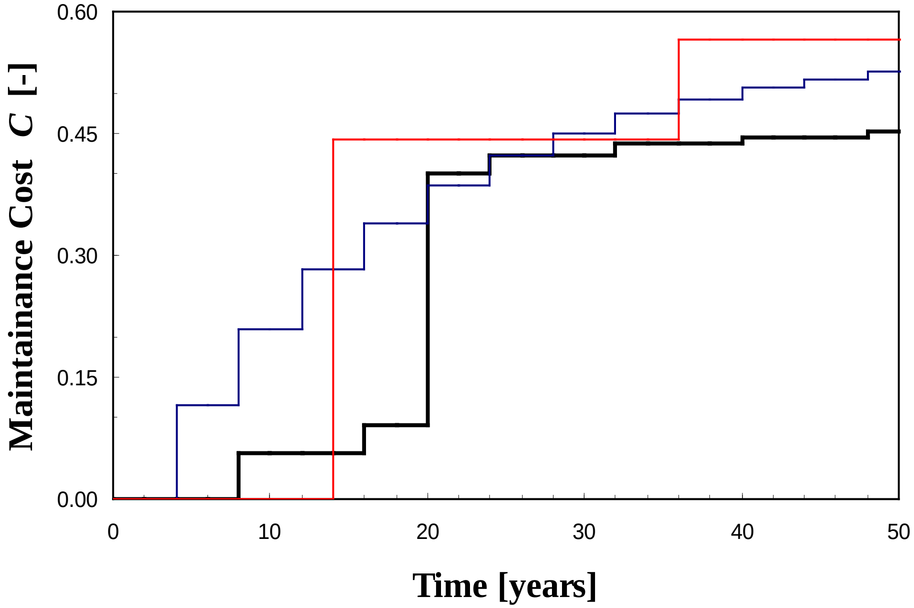
Maintenance Scenarios



Optimal Maintenance

$$\min\left\{ C(\Delta\beta,\Delta t) \,\middle|\, \beta \geq \beta_{target} \right\}$$





Conclusions (I)

- Damage processes in concrete bridges are usually investigated based on **simplified models of diffusion processes** and through the study of the **local deterioration of the materials**, concrete and steel, with limited attention paid to the global effects of these local phenomena on the overall performance of the structural system.

- This is clearly not consistent with the actual nature of the problem, since the simulation of diffusion processes should be able to account for **complex geometrical and mechanical boundary conditions**, which generally characterize engineering applications.

- Moreover, the **local deterioration mechanisms interact with the global structural response**. As a consequence, the **structural scheme** plays a fundamental role in the assessment of deteriorating structures, particularly for redundant systems, where damage may lead to time-variant redistributions of the internal actions.

Conclusions (II)

- These aspects can be consistently taken into account by means of the proposed **general methodology** for **life-cycle reliability assessment**, **maintenance** and **rehabilitation** of concrete structures exposed to the **diffusive attack from environmental aggressive agents**, with emphasis on **concrete bridges under corrosion**.

- The proposed **probabilistic formulation** allows:

1. To evaluate the **time-variant structural reliability** or, conversely, the **remaining service life** which can be assured under prescribed reliability levels without maintenance (**ASSESSMENT**).

2. To plan a **rehabilitation of the structure** in order to achieve a prescribed target value of the service life (**REHABILITATION**).

3. To select an **optimal maintenance scenario** among different economic alternatives (**MAINTENANCE**).

IABMAS Italy Group

Foundation Meeting

IABMAS 2012 – The Sixth International Conference on Bridge Maintenance, Safety and Management

Stresa, Lake Maggiore, Italy | *July 9th, 2012*

POLITECNICO DI MILANO

Ispezione, Manutenzione, Sicurezza e Gestione dei Ponti

Bridge Inspection, Maintenance, Safety and Management

1° Workshop Gruppo Italiano IABMAS

Politecnico di Milano, 14-15 Ottobre 2013

http://www.iabmas-italy.it

Gruppo Italiano IABMAS
IABMAS Italian Group

Obiettivi | IABMAS | Gruppo Italiano | Membri | Attività | Contatti

http://www.iabmas-italy.it

55th Brazilian Congress on Concrete

3rd Symposium on Subway, Railway and Highway Infrastructure

Gramado, Rio Grande do Sul, Brazil

November 1st, 2013

POLITECNICO DI MILANO

Thank you for kind attention!