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)
“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.”
Italian Networks:

- Railways 16,000 km
- Highways 3,400 km
- Roads 26,700 km
The condition rating of stocks of existing bridges and infrastructure networks indicates that the \textit{economic impact of deterioration} is exceptionally high and emphasizes the importance of proper maintenance and repair of structurally deficient bridges.

These problems present a \textit{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 \textit{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 \textit{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 \textit{probabilistic terms}. 
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
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
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

Target Reliability

Reliability Index $\beta$

Time $t$

$T$

Structure and Infrastructure Engineering, 7(1-2), 2011

Structure and Infrastructure Engineering, 31, 2009

Structural Safety, 4(5), 2008

Probabilistic Engineering Mechanics, 23(4), 2008

Structural Engineering International, IABSE, 16(3), 2006


Journal of Structural Engineering, ASCE, 130(11), 2004
Research Cooperation
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

\[ p = 2x \quad \delta = \frac{p}{D_0} \]

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

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

\[ \delta_s = \delta(2 - \delta) \]
Pitting Corrosion

\[ R = \frac{x_{\text{max}}}{\bar{x}} \]

R = 4 – 8 (natural corrosion)
R = 5 – 13 (accelerated corrosion)

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

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

\[
\delta_{s2} = \frac{2\delta^2}{\pi} (\theta_2 - \beta)
\]

\[
\beta = \frac{b_0}{D_0} = 2\delta \sqrt{1 - \delta^2}
\]

Val - Melchers

Rodriguez

\[ p = x_{\text{max}} \]

\[ \delta = \frac{p}{D_0} \]
Reduction of Steel Ductility

(Almusallam et al., 2001)

\( \varepsilon_{su}(t)/\varepsilon_{su}(0) \) vs. Elongation (mm)

\( \delta_s(t) \) vs. Duration of accelerated salt spray corrosion [Days]

\[ \begin{align*}
\varepsilon_{su} &= \begin{cases} 
\varepsilon_{su0}, & 0 \leq \delta_s < 0.016 \\
0.1521\delta_s^{-0.4583}\varepsilon_{su0}, & 0.016 < \delta_s \leq 1 
\end{cases}
\end{align*} \]

- (1) Almusallam (2001)
- (2) Kobayashi (2006)
- (3) Apostolopoulos & Papadakis (2008)
Deterioration of Concrete (1/2)

Longitudinal cracking and spalling of concrete cover

\[ A_c = [1 - \delta_c(\delta)] A_{c0} \]
\[ f_c = [1 - \delta_c(\delta)] f_{c0} \]

Scaling
Delamination
Border effects

[Zhang et al. 2009]
\[ f_c = [1 - \delta_c(\delta)] f_{c0} \]

(Vecchio & Collins, 1986)

\[ f_c = \frac{f_{c0}}{1 + \kappa \frac{\epsilon_\perp}{\epsilon_{c0}}} \]

\[ n_{\text{bars}} = 6 \]

\[ b_i \]

\[ \epsilon_\perp = \frac{\Delta b}{b_i} = \frac{n_{\text{bars}} w}{b_i} \]

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

\[ \delta_{s0} = 1 - \left[ 1 - \frac{R}{D_0} \left( 7.53 + 9.32 \frac{c_0}{D_0} \right) \times 10^{-3} \right]^2 \]
**STRUCTURAL ANALYSIS OF DAMAGED REINFORCED CONCRETE SECTIONS**

\[ r(t) = H(t) \mathbf{e}(t) \]

- \( r = r(t) = [N \ M_x \ M_y]^T \) 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 \( t \)

\[ H(t) = H_c(t) + H_s(t) = \int_{A_c} E_c(x, y, t) \mathbf{b}(x, y)^T \mathbf{b}(x, y) \delta_c'(x, y, t) \, dA + \sum_k E_{sk}(t) \mathbf{b}_k^T \mathbf{b}_k \delta_{sk}'(t) A_{sk} \]
Deteriorating R.C. Beam Element

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

\[ H(x,t) = H_c(x,t) + H_s(x,t) \]

\[ f(t) = K(t)s(t) \]

\[ K(t) = K_M(t) + K_G(t) \]

\[ K_M(t) = \int_0^t B^T H(t) B \, dx = K_c(t) + K_s(t) \]

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)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beam 111</th>
<th>Beams 114-116</th>
<th>Beam 311</th>
<th>Beams 313-316</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{cc}$ [MPa]</td>
<td>50</td>
<td>34</td>
<td>49</td>
<td>37</td>
</tr>
<tr>
<td>$f_{ct}$ [MPa]</td>
<td>4.1</td>
<td>3.1</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>$E_c$ [GPa]</td>
<td>37.3</td>
<td>33.8</td>
<td>37.1</td>
<td>34.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Φ 8 bars</th>
<th>Φ 10 bars</th>
<th>Φ 12 bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{sy}$ [MPa]</td>
<td>615</td>
<td>575</td>
<td>585</td>
</tr>
<tr>
<td>$f_{su}$ [MPa]</td>
<td>673</td>
<td>655</td>
<td>673</td>
</tr>
<tr>
<td>$E_s$ [GPa]</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
</tbody>
</table>
### Mean penetration depth [mm] (maximum value)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Tension bars</th>
<th>Compression bars</th>
<th>Stirrups</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td>0.45 (1.1)</td>
<td>0.52</td>
<td>0.39 (3.1)</td>
</tr>
<tr>
<td>115</td>
<td>0.36 (1.0)</td>
<td>0.26</td>
<td>0.37 (3.0)</td>
</tr>
<tr>
<td>116</td>
<td>0.71 (2.1)</td>
<td>0.48</td>
<td>0.66 (5.0)</td>
</tr>
<tr>
<td>313</td>
<td>0.30 (1.3)</td>
<td>0.20</td>
<td>0.35 (2.8)</td>
</tr>
<tr>
<td>314</td>
<td>0.48 (1.5)</td>
<td>0.26</td>
<td>0.50 (4.0)</td>
</tr>
<tr>
<td>316</td>
<td>0.42 (1.8)</td>
<td>0.37</td>
<td>0.54 (4.3)</td>
</tr>
</tbody>
</table>
Numerical Validation – Results

![Graph showing load vs. displacement with experimental and numerical results compared. The graph includes data points labeled 111, 114, 115, 116. A color gradient representing strain is also shown on the right side of the image.](image-url)
Numerical Validation – Results

Load [kN] vs. Displacement [mm] graph with experimental and numerical data comparing different scenarios.

- Experimental data
- Numerical data

Load distribution with color coding for $\delta_c$. 

4Ø8
4Ø12
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 Indices of the Materials

\[ 0 \leq \delta(t) \leq 1 \]

- 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

\[ \frac{\partial \delta(t)}{\partial t} \]
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)

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

- Concentration
- Diffusivity
- Time

- Simplified approach – Solution of the 1D problem

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

Model Code for Service Life Design
fib Bulletin No. 34, 2006
Validation of the Diffusion Model
Validation of the Diffusion Model

![Diagram showing 8 vacuum chambers with dimensions and diffusion model plots.]
Coupling between Diffusion and Damage

Stochastic Effects and Evolutionary Rule

\[ D = (1 + \Psi) \cdot D_0 \]

(A) Symmetrical \( \Psi \)-Distributions in Uncracked Concrete

(B) Skewed \( \Psi \)-Distributions in Cracked Concrete

\[ f_\psi(\psi) = \frac{2}{\psi_b - \psi_a} \]

\( \psi_a = -\psi_b \)

\( \psi_c = 0 \)

non cracked concrete

\[ f_\psi(\psi) = \frac{2}{\psi_b - \psi_a} \]

\( \psi_c \)

cracked concrete
Continuous T-Beam

- $L = 3.00 \text{ m}$
- $H = 0.40 \text{ m}$
- $h = 0.25 \text{ m}$
- $b = 0.15 \text{ m}$
- $g = 10 \text{ kN/m}$

**Diagram Details:**
- $L$ = Length
- $H$ = Height
- $h$ = Height of the beam
- $b$ = Width of the beam
- $g$ = Load per unit length
Diffusion and Mechanical Damage
Life-Cycle Performance

Section A

Section B
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 $\Theta = R / S$ is no lower than unity:

$$\Theta \geq 1$$
The probability of failure $P_F$, or the reliability index $\beta$, can be evaluated by the integration of the density function $f_\Theta(\theta)$ within the failure domain $D$:

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

$D = \{ \theta \mid \theta < 1 \}$
Residual Lifetime

\[ T = \min \left\{ (t - t_0) \mid \beta \geq \beta^* \right\} \]
Arch Bridge
### Characteristics of the Cross-Sections

<table>
<thead>
<tr>
<th>Span</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_s'$</td>
<td>21Ø28</td>
<td>48Ø28</td>
<td>42Ø28</td>
<td>30Ø28</td>
<td>24Ø28</td>
<td>48Ø28</td>
<td>48Ø28</td>
<td>45Ø28</td>
<td>33Ø28</td>
</tr>
<tr>
<td></td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
<td>130Ø8</td>
</tr>
<tr>
<td>$A_s$</td>
<td>21Ø28</td>
<td>30Ø28</td>
<td>42Ø28</td>
<td>24Ø28</td>
<td>24Ø28</td>
<td>21Ø28</td>
<td>36Ø28</td>
<td>27Ø28</td>
<td>24Ø28</td>
</tr>
</tbody>
</table>
Characteristics of the Cross-Sections

![Graphs showing bending moment and axial force vs. abscissa and axial force]

- Bending Moment $M$ [MNm]
  - Abscissa $x$ [m]
  - $3/4 \alpha$, $\alpha/2$, $\alpha/2$, $\alpha$

- Bending Moment $M$ [MNm]
  - Axial Force $N$ [MN]
Limit Analysis of the Bridge

Collapse Mechanism

\( \lambda_c = 4.28 \)
Concentration Maps

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

```
<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4a</td>
<td>a/2</td>
<td>a/2</td>
<td>a</td>
<td></td>
</tr>
</tbody>
</table>
```

```
Time-variant Performance

![Graph showing the relationship between Axial Force and Bending Moment](image-url)
$t = 0$ years

Axial Force

Bending Moment

Collapse Mechanism ($\lambda_c = 4.28$)

$t = 50$ years

Axial Force

Bending Moment

Collapse Mechanism ($\lambda_c = 1.42$)
$t = 50$ years
($\lambda_c = 1.42$)
Probabilistic Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution Type</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\Delta x, \Delta y)$</td>
<td>Normal</td>
<td>$0$</td>
<td>$50 \text{ mm}$</td>
</tr>
<tr>
<td>$k$</td>
<td>Lognormal</td>
<td>$k_{\text{nom}}$</td>
<td>$0.20 \cdot k_{\text{nom}}$</td>
</tr>
<tr>
<td>$g$</td>
<td>Normal</td>
<td>$g_{\text{nom}}$</td>
<td>$0.10 \cdot g_{\text{nom}}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Normal</td>
<td>$\rho_{\text{nom}}$</td>
<td>$0.40 \cdot \rho_{\text{nom}}$</td>
</tr>
</tbody>
</table>

$\beta = \frac{\lambda_{\theta}}{\zeta_{\theta}} = 7.62$
Probabilistic Lifetime Assessment

- Collapse Multiplier $\lambda_c$
- Time [years]
- Service Life $T$ [years]
- Load Multiplier $\lambda$

$P^* \rightarrow 0$
$P^* \rightarrow 1$

- $P^* = 0.50$
- 0.25-0.75
- 0.00-1.00
Design Lifetime

Reliability Index $\beta$

$\beta_0$

$\beta^*$

Time $t$

$T_d$

$T \geq T_d$

Target Reliability

Design Strategy 1

Design Strategy 2

$T_d$
Arch Bridge

Bridge over the Breggia river (Cernobbio, Italy)
Damage State

- Concrete Spalling
- Steel Corrosion
- Deck Deterioration
Structural Model

Bridge

Deck

Arches

Ties
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

Deck

Ties
Repair Intervention
Role of Maintenance

Reliability Index $\beta$

- $\beta_0$
- $\beta^*$
- Preventive maintenance
- Essential maintenance
- Without maintenance
- Target Reliability

Time $t$

$T$, $T_P$, $T_{P+E}$
Certosa Cable-Stayed Bridge

Deck Cross-sections

Straight cross-section.

Skewed cross-section.

Skewed cross-section on the transversal beam.
spalling and initial steel corrosion

Pylons
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

86 Ø26 steel bars

$\eta = 2,50$ m

$dz = 1,14$ m

$C_0$

Aggressive Agent

Grid of the Automaton
Concentration Maps

$C(x,t)/C_0$

(a) Damaged Structure

(b) Rehabilitated Structure
Time-variant Performance

- Damaged Structure
- Rehabilitated Structure

- Dimensionless Curvature $\Delta \varepsilon_z [-]$
- Dimensionless Bending Moment $m_z [-]$
- Yielding Moment $m_y$

Time [year]:

0 10 20 30 40 50
### Probabilistic Model

<table>
<thead>
<tr>
<th>Random Variable ((t=t_0))</th>
<th>Type</th>
<th>(\mu)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete strength (f_c)</td>
<td>Lognormal</td>
<td>(f_{c,nom})</td>
<td>5 MPa</td>
</tr>
<tr>
<td>Steel strength (f_{sy})</td>
<td>Lognormal</td>
<td>(f_{sy,nom})</td>
<td>30 MPa</td>
</tr>
<tr>
<td>Coordinates of the nodal points ((y_i, z_i))</td>
<td>Normal</td>
<td>((y_i, z_i)_{nom})</td>
<td>5 mm</td>
</tr>
<tr>
<td>Coordinates of the steel bars ((y_m, z_m))</td>
<td>Normal</td>
<td>((y_m, z_m)_{nom})</td>
<td>5 mm</td>
</tr>
<tr>
<td>Diameter of the steel bars (\varnothing_m)</td>
<td>Normal</td>
<td>(\varnothing_{m,nom})</td>
<td>0.10 (\varnothing_{m,nom})</td>
</tr>
<tr>
<td>Diffusivity coefficient (D)</td>
<td>Normal</td>
<td>(D_{nom})</td>
<td>0.10 (D_{nom})</td>
</tr>
<tr>
<td>Concrete damage rate (q_c)</td>
<td>Normal</td>
<td>(q_{c,nom})</td>
<td>0.30 (q_{c,nom})</td>
</tr>
<tr>
<td>Steel damage rate (q_s)</td>
<td>Normal</td>
<td>(q_{s,nom})</td>
<td>0.30 (q_{s,nom})</td>
</tr>
</tbody>
</table>
Probabilistic Time-variant Performance

Damaged Structure

Rehabilitated Structure

Yielding Moment $m_y$

Time [year]

Probabilistic Time-variant Performance
Maintenance Costs

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

\[ C_i = \alpha \Delta\beta_i \]

\[ C = \sum_{i=1}^{n} \frac{C_i}{(1 + \nu)^{t_i}} = \sum_{i=1}^{n} C_{0i} \]

- \( \Delta\beta_i = \) modification of the reliability index associated with the intervention \( i=1, \ldots, n \) 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 \( t_0 \)
- \( \nu = \) Discount rate
Structural Model and Exposure Scenario

\[ y \uparrow \quad \rightarrow \quad z \]

\[ C_0 \]

\[ \frac{1}{2} C_0 \]

- Aggressive Agent
- Grid of the Automaton
Concentration Maps

$t = 10 \text{ years}$  
$t = 20 \text{ years}$  
$t = 30 \text{ years}$  
$t = 40 \text{ years}$  
$t = 50 \text{ years}$

$C(x,t)/C_0$

- $1.00$
- $0.90$
- $0.80$
- $0.70$
- $0.60$
- $0.50$
- $0.40$
- $0.30$
- $0.20$
- $0.10$
- $0.00$
Resistance Domains $M_y-M_z$

Resistant Moment $m_z$

$t = 0$ years

$t = 50$ years

Resistant Moment $m_r$

$m_y = \frac{M_y}{(f_c A_0 dz)}$

$m_z = \frac{M_z}{(f_c A_0 dy)}$

$N = -100$ MN

($\Delta t = 2$ years)
### Probabilistic Model

<table>
<thead>
<tr>
<th>Random Variable ( (t=t_0) )</th>
<th>Type</th>
<th>( \mu )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete strength ( f_c )</td>
<td>Lognormal</td>
<td>( f_{c,\text{nom}} )</td>
<td>5 MPa</td>
</tr>
<tr>
<td>Steel strength ( f_{sy} )</td>
<td>Lognormal</td>
<td>( f_{sy,\text{nom}} )</td>
<td>30 MPa</td>
</tr>
<tr>
<td>Coordinates of the nodal points ( (y_i, z_i) )</td>
<td>Normal</td>
<td>( (y_i, z_i)_{\text{nom}} )</td>
<td>5 mm</td>
</tr>
<tr>
<td>Coordinates of the steel bars ( (y_m, z_m) )</td>
<td>Normal</td>
<td>( (y_m, z_m)_{\text{nom}} )</td>
<td>5 mm</td>
</tr>
<tr>
<td>Diameter of the steel bars ( \varnothing_m )</td>
<td>Normal</td>
<td>( \varnothing_{m,\text{nom}} )</td>
<td>0.10 ( \varnothing_{m,\text{nom}} )</td>
</tr>
<tr>
<td>Diffusivity coefficient ( D )</td>
<td>Normal</td>
<td>( D_{\text{nom}} )</td>
<td>0.10 ( D_{\text{nom}} )</td>
</tr>
<tr>
<td>Concrete damage rate ( q_c )</td>
<td>Normal</td>
<td>( q_{c,\text{nom}} )</td>
<td>0.30 ( q_{c,\text{nom}} )</td>
</tr>
<tr>
<td>Steel damage rate ( q_s )</td>
<td>Normal</td>
<td>( q_{s,\text{nom}} )</td>
<td>0.30 ( q_{s,\text{nom}} )</td>
</tr>
</tbody>
</table>

\[
\beta = \beta(t)
\]

**Acting Moment**

\[
\begin{align*}
\mu &= 0.050 \\
\sigma &= 0.10 \mu
\end{align*}
\]
Maintenance Scenarios

Essential Maintenance

Preventive Maintenance

$C_E/C_P = 10$

$\nu = 0.06$
Optimal Maintenance

\[
\min \left\{ C(\Delta \beta, \Delta t) \mid \beta \geq \beta_{\text{target}} \right\}
\]
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
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
Thank you for kind attention!