



## **Seismic Resilience of Aging Bridges and Evolving Road Networks**

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## **Outline**

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- 1. Introduction and Motivation**
- 2. Aging and Deterioration of RC Bridges under Corrosion**
- 3. Lifetime Seismic Assessment of Deteriorating Bridges**
- 4. Post-event Road Network Management**
- 5. Functionality and Resilience Analysis of Road Networks**
- 6. Application: RC Bridges and Evolving Highway Networks**
- 7. Conclusions**



## Post-Earthquake Emergency Response

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- Road infrastructure networks play an important role in the emergency response to seismic events and related hazards.
- Bridges are the most vulnerable components of road networks, and their damage may involve direct economic losses due to repair interventions, as well as indirect losses due to traffic delay and network downtime.



Bay Bridge – Loma Prieta earthquake (1989)



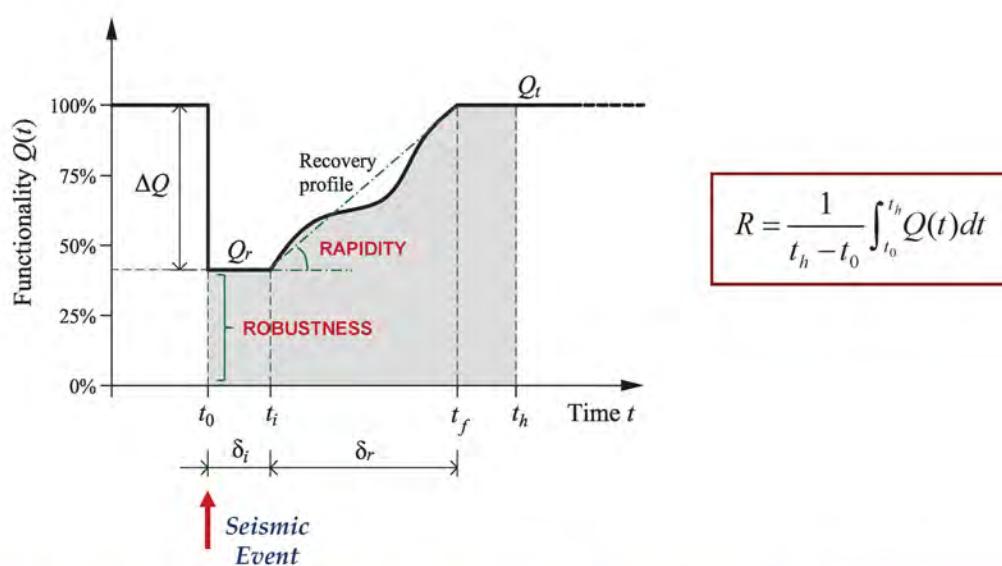
Cypress Viaduct – Loma Prieta earthquake (1989)



## Measure of Resilience

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- **Resilience** is the ability of a system to withstand the effects of disruptive events and to recover promptly and efficiently the pre-event functionality.





# Resilience of Bridges and Networks

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- Framework to integrate the **seismic assessment** of bridge structures and the post-event **network analysis** for the evaluation of **network functionality** and **seismic resilience** under uncertainty.

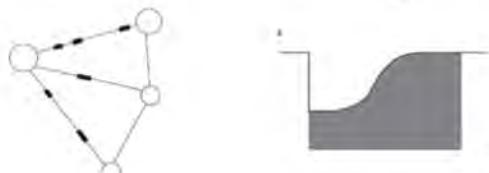
- (1) Probabilistic approach to **bridge seismic assessment**



- (2) Quantification of road **network functionality**



- (3) Probabilistic assessment of **network seismic resilience**



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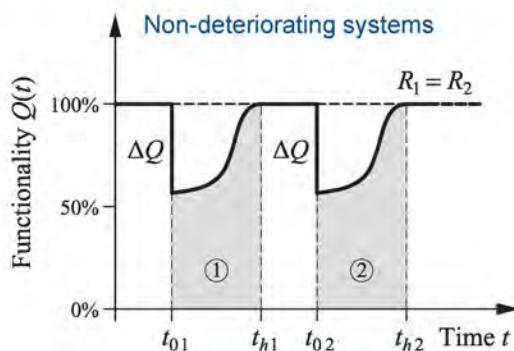


# Resilience of Deteriorating Systems

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**SEISMIC HAZARD**  
(earthquakes)

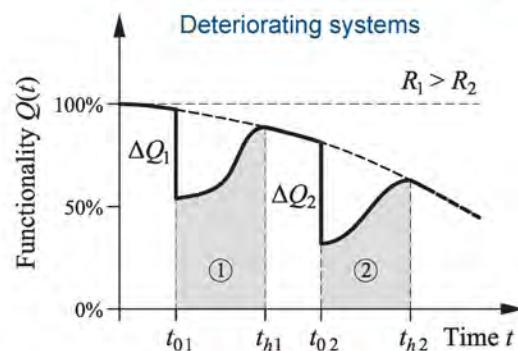
Sudden loss of functionality



$$R = \text{const.}$$

+ **ENVIRONMENTAL HAZARD**  
(concrete structures: corrosion)

Continuous loss of functionality



$$R = R(t_0)$$

Biondini, F., Camnasio, E. Titi, A., 2015. Seismic resilience of concrete structures under corrosion, *Earthquake Engineering and Structural Dynamics*, Wiley, 44(14), 2445–2466.

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# RC Bridges: Corrosion of Reinforcement

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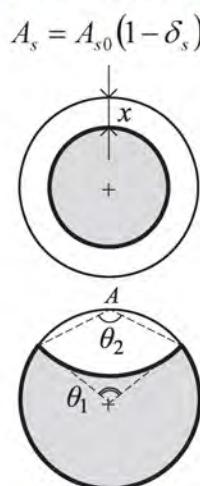
- The experimental evidence shows that the **main effects of corrosion** of steel reinforcement in concrete structures include:
1. **Steel mass loss**, with reduction of the resistant cross-section of the reinforcing steel bars.
  2. **Reduction of steel ductility**, which may lead to brittle failures.
  3. **Deterioration of concrete**, due to formation of oxidation products which may lead to propagation of splitting cracks.



# Corrosion Modeling

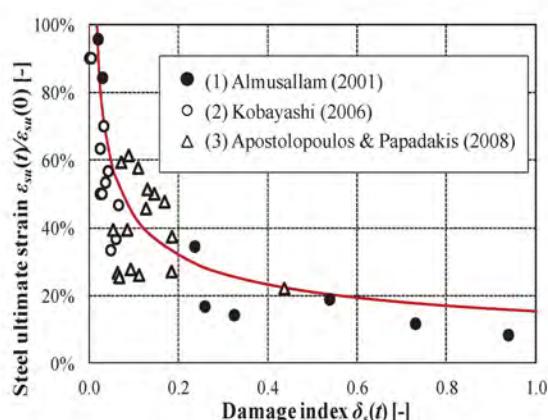
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## REDUCED STEEL BAR AREA



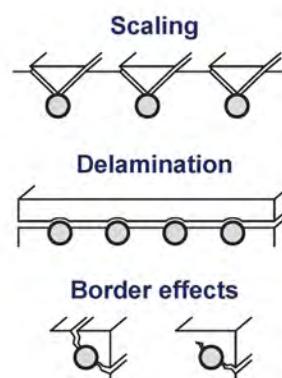
## REDUCED STEEL ULTIMATE STRAIN

$$\varepsilon_{su} = \varepsilon_{su}(\delta_s)$$



## REDUCED CONCRETE STRENGTH

$$f_c = f_c(\delta_s)$$





## Diffusion Process and Corrosion Rate

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### ➤ Fick's second law (1D, 2D, 3D)

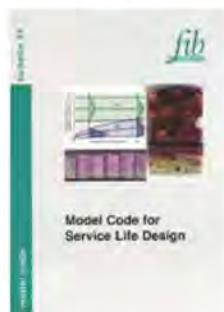
$$\nabla^2 C = \frac{1}{D} \cdot \frac{\partial C}{\partial t}$$

$C$  = Concentration

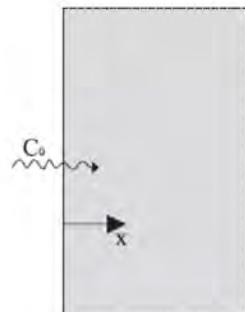
$D$  = Diffusivity

$t$  = Time

### ➤ Simplified approach – Solution of the 1D problem



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



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

Titi, A. & Biondini, F. 2016. On the accuracy of diffusion models for life-cycle assessment of concrete structures, *Structure and Infrastructure Engineering*, 12(9), 1202–1215.

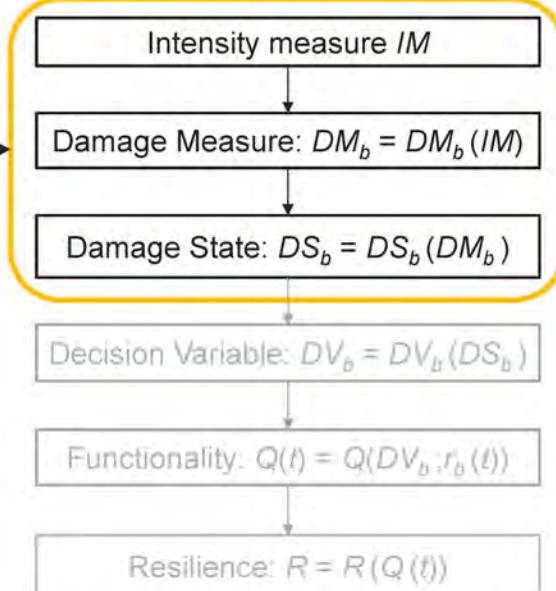
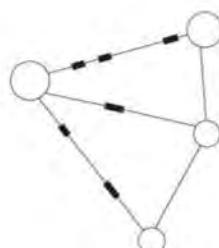


## Seismic Assessment of Bridges

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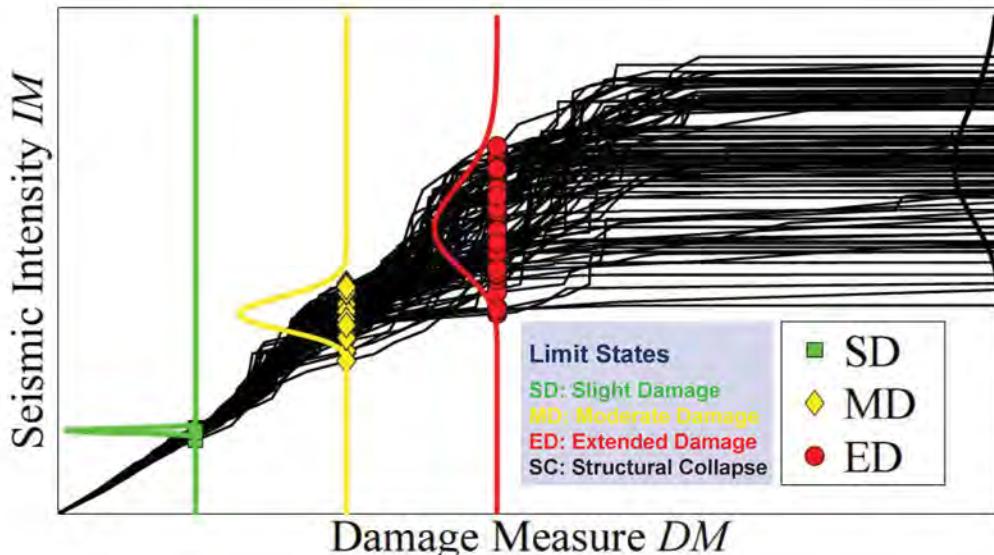


Seismic assessment of bridge structures





## Limit States and Seismic Capacity (IDA)<sup>11</sup>

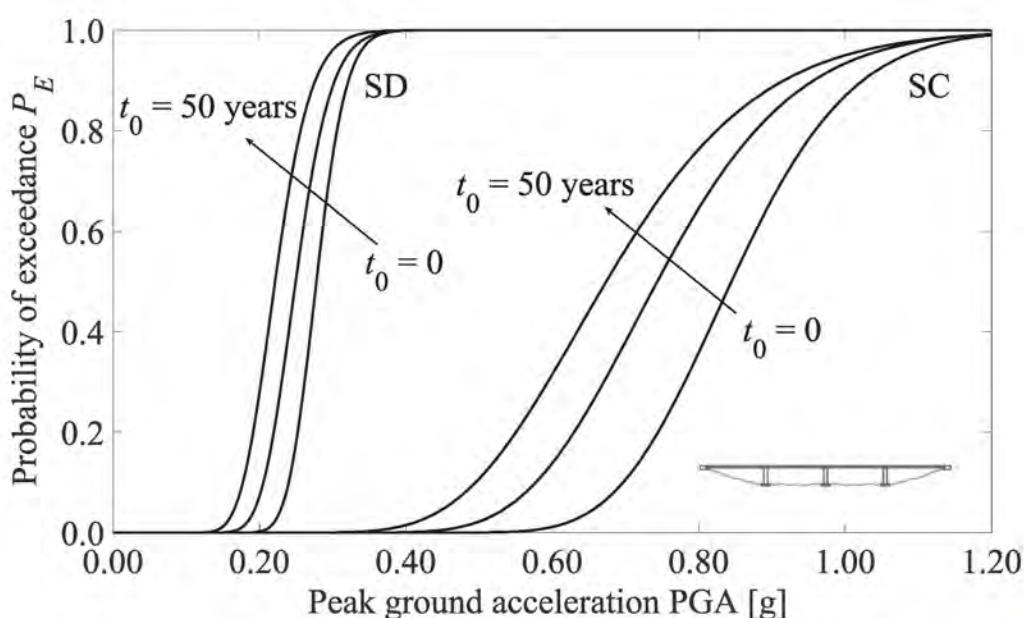


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## Lifetime Fragility Analysis<sup>12</sup>



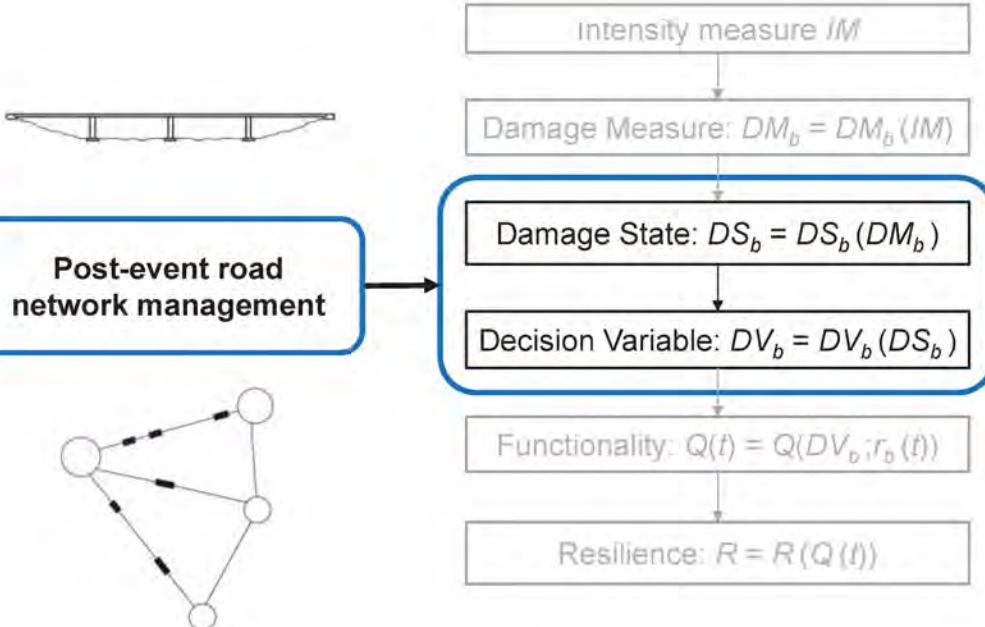
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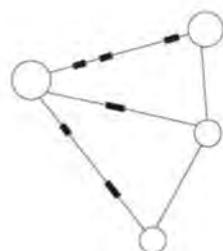
# Post-Event Network Management

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# Type of Users and Traffic Restrictions

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DV	Objective name	ND	SD	MD	ED	SC
0	Immediate access	X	-	-	-	-
1	Weight restriction	-	X	-	-	-
2	One lane open only	-	-	X	-	-
3	Emergency access only	-	-	-	X	-
4	Closed	-	-	-	-	X

K. R. Mackie and B. Stojadinovic. Post-earthquake functionality of highway overpass bridges. *Earthquake Engineering and Structural Dynamics*, 35(1):77–93, 2006.



$$\begin{cases} f_h = 0 \text{ and } \tilde{v}_{\max} < v_{\max,0} & , DV_b = 1 \\ n_L = 1 & , DV_b = 2 \\ f_l = 0 & , DV_b = 3 \\ f_e = 0 \text{ or } n_L = 0 & , DV_b = 4 \end{cases}$$



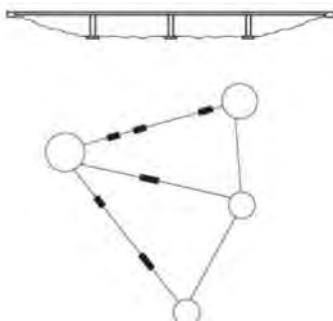
$f_{l,h,e}$  = flow per unit of time (light/heavy/emergency vehicles)

$v_{\max}$  = maximum speed;  $n_L$  = number of lanes

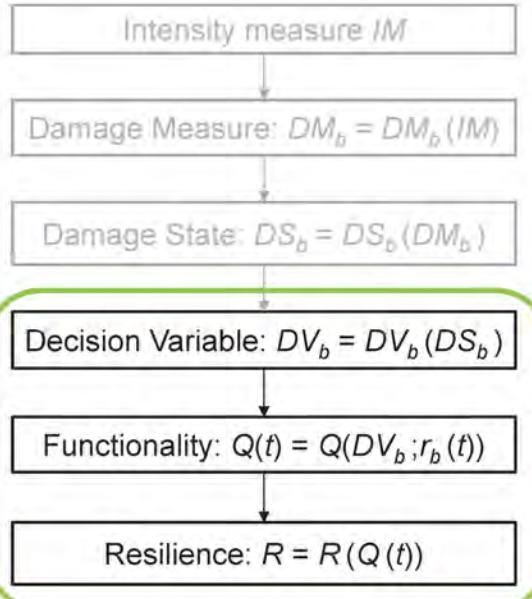


# Network Functionality and Resilience

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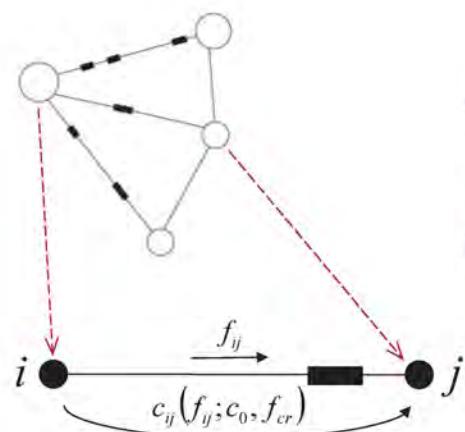


**Functionality and resilience assessment of road networks**



# Traffic Analysis and Functionality Levels

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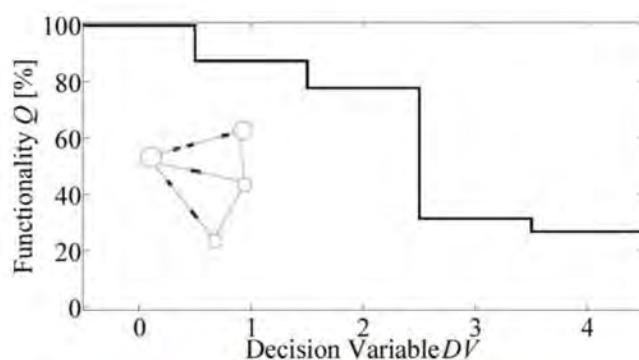
$$\text{Total Travel Time: } TTT = \sum_{i \in I} \sum_{j \in J} \int_0^{f_{ij}} c_{ij}(f) df$$

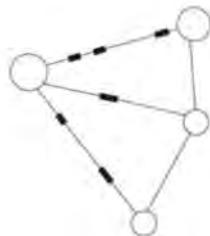
$$\text{System functionality: } Q(DV_b; t) = \frac{TTT_u}{TTT_d(DV_b; t)}$$

**Arc Travel Time:**

$$c_{ij} = c_0 \left[ 1 + \alpha \cdot \left( \frac{f_y}{f_{cr}} \right)^\beta \right]$$

$$c_0 = \frac{L}{v_{\max}} \quad f_{cr} = \frac{v_{cr}}{d_{\min}} \cdot n_r$$

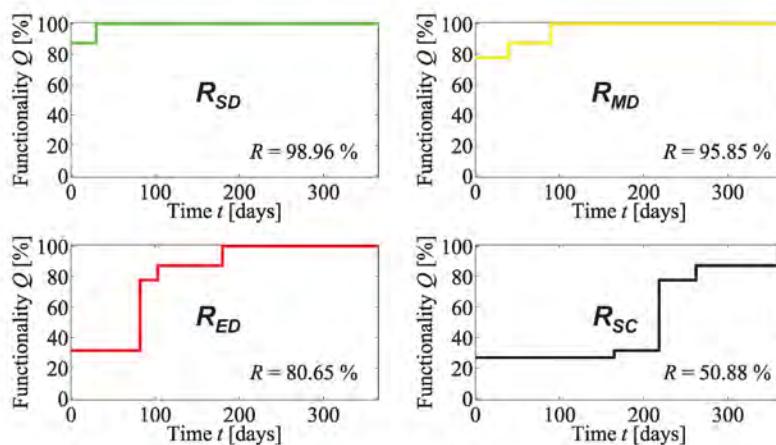




$$R(t_0) = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t) dt$$

$$\int_{t_0}^{t_h} Q(t) dt = \sum_{\Delta t_{h,i}} Q_{\Delta t_{h,i}} \Delta t_{h,i}$$

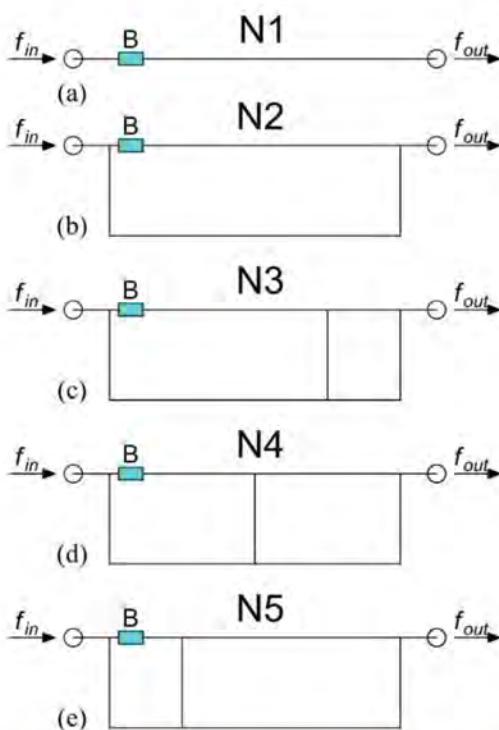
$$R(IM, t_0) = \sum_{i=0}^{N_{DS}} P_{DS,i}(IM, t_0) \cdot R_i$$



DS / capacity threshold	$r_1$	$r_2$	$r_3$	$r_4$
<b>SD</b>	$r_{1,SD}$	-	-	-
<b>MD</b>	$r_{1,MD}$	$r_{2,MD}$	-	-
<b>ED</b>	$r_{1,ED}$	$r_{2,ED}$	$r_{3,ED}$	-
<b>SC</b>	$r_{1,SC}$	$r_{2,SC}$	$r_{3,SC}$	$r_{4,SC}$



## Application: Highway Networks



Bridge Unit (one or more bridges)

### HIGHWAY NETWORKS

N1 *isolated*

N2 *with detour route*

N3 *with detour and "far" re-entry link*

N4 *with detour and "medium distance" re-entry link*

N5 *with detour and "close" re-entry link*

Traffic Parameters	Highway Road	Secondary Road	Re-entry Link
Length $L$ [km]	10	40	1
No. of lanes $n_L$	3	2	1
Max. speed $v_{max}$ [km/h]	130	90	90
Min. speed $v_{min}$ [km/h]	70	50	50
Critical speed $v_{cr}$ [km/h]	65	65	65
Min. distance $d_{min}$ [m/cars]	30	30	30

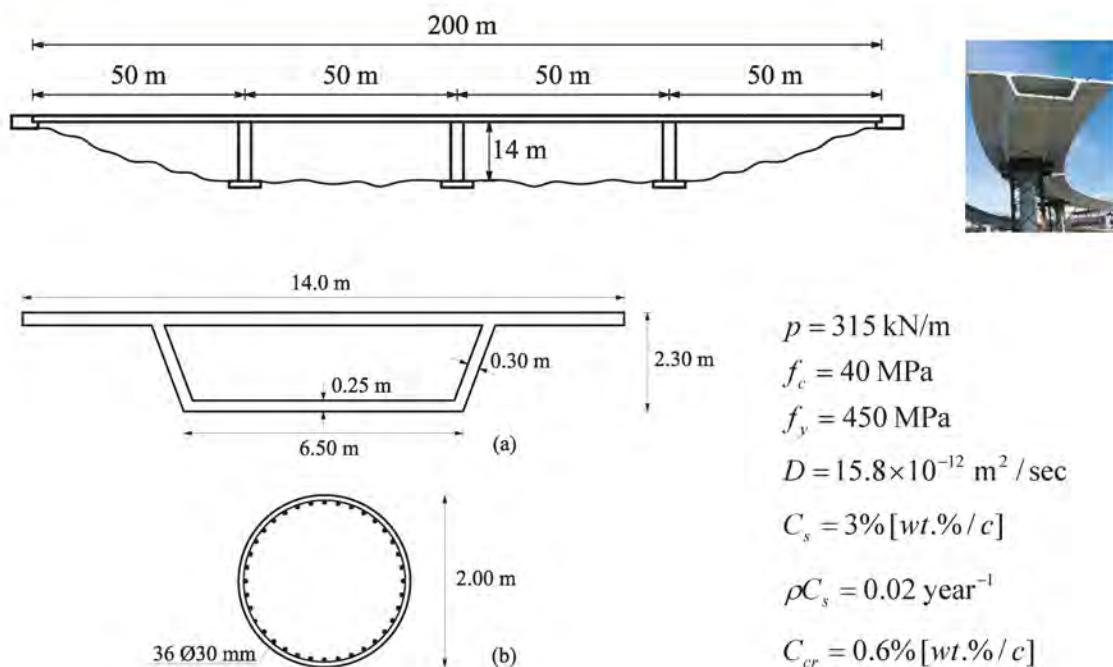
$$f_i = 7000 \text{ cars/h}; f_h = 1000 \text{ cars/h}; f_e = 700 \text{ cars/h}$$

Adapted from: AISCAT, Associazione Italiana Società Concessionarie Autostrade e Trafori.



# RC Bridge under Corrosion

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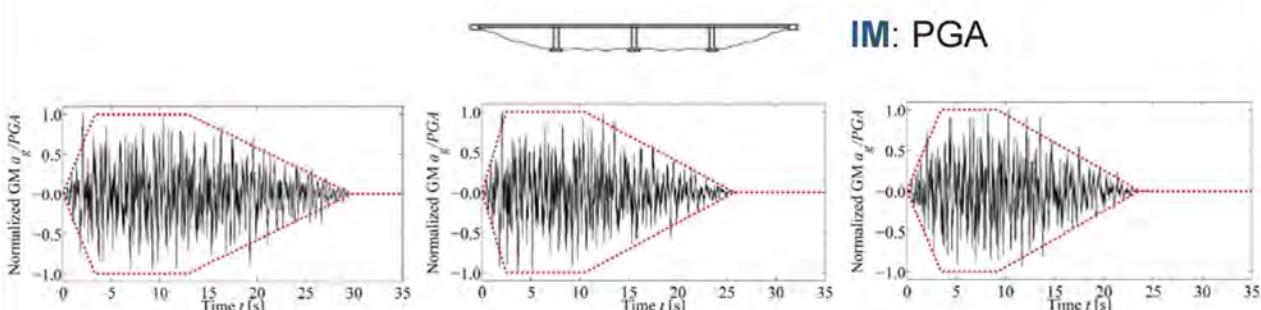
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# Probabilistic Model

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Probability distributions and coefficients of variation.

Random Variable ( $t = 0$ )	Distribution	C.o.V.
Concrete strength, $f_c$	Lognormal	$5 \text{ MPa}/f_{c,\text{nom}}$
Steel strength, $f_{sy}$	Lognormal	$30 \text{ MPa}/f_{sy,\text{nom}}$
Viscous damping, $\xi$	Normal (*)	0.40
Diffusivity, $D$	Normal (*)	0.20
Damage rate, $q_s$	Normal (*)	0.30
Chloride concentration, $C_0$	Normal (*)	0.30
Critical concentration, $C_{cr}$	Beta (**)	0.15

(\*) Truncated distribution with non-negative outcomes.

(\*\*) Lower bound  $b_{\min} = 0.2$ . Upper bound  $b_{\max} = 2.0$ .

Latin Hypercube Sampling

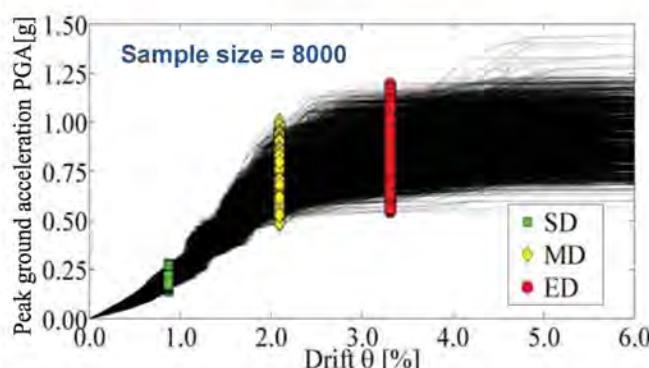
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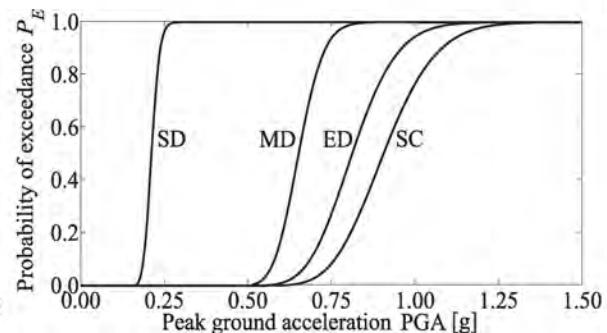
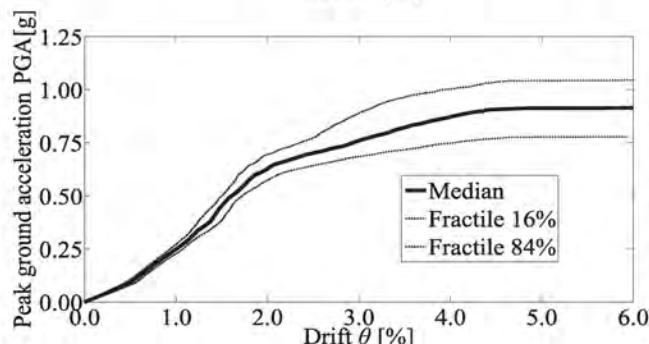


## Fragility Analysis

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DM: Drift  $\theta$ 

Damage state	DM threshold
ND	-
SD	$\theta_y$
MD	$\theta_y + 0.3 \theta_p$
ED	$\theta_y + 0.6 \theta_p$
SC	Dynamic instability

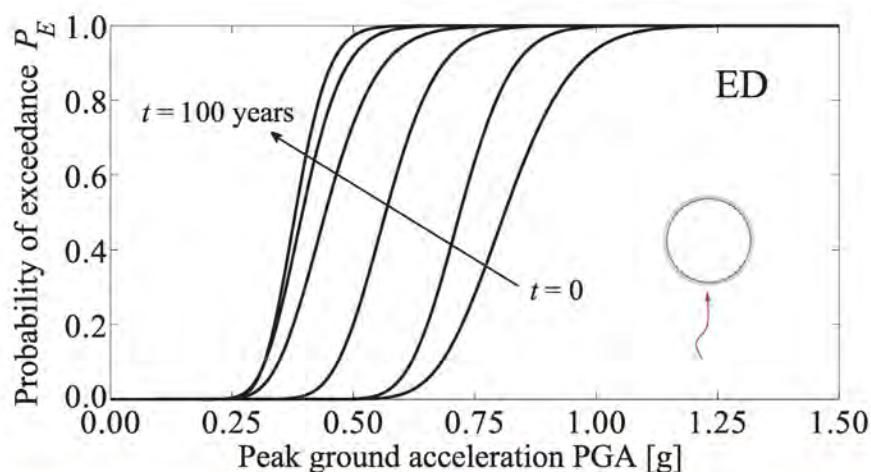


## Time-variant Fragility Curves

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Time-variant Mean Seismic Capacities

$t$ [years]	SD	MD	ED	SC
0	0.212	0.679	0.819	0.894
10	0.217	0.626	0.726	0.747
25	0.224	0.552	0.573	0.576
50	0.252	0.446	0.451	0.451
75	0.272	0.399	0.401	0.401
100	0.278	0.383	0.384	0.385

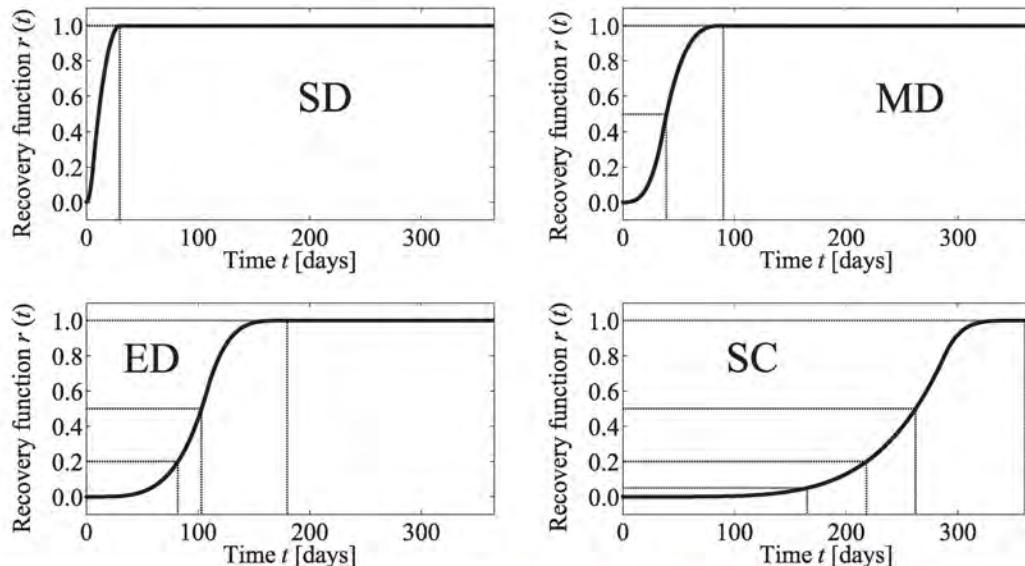




# Bridge Recovery Profiles

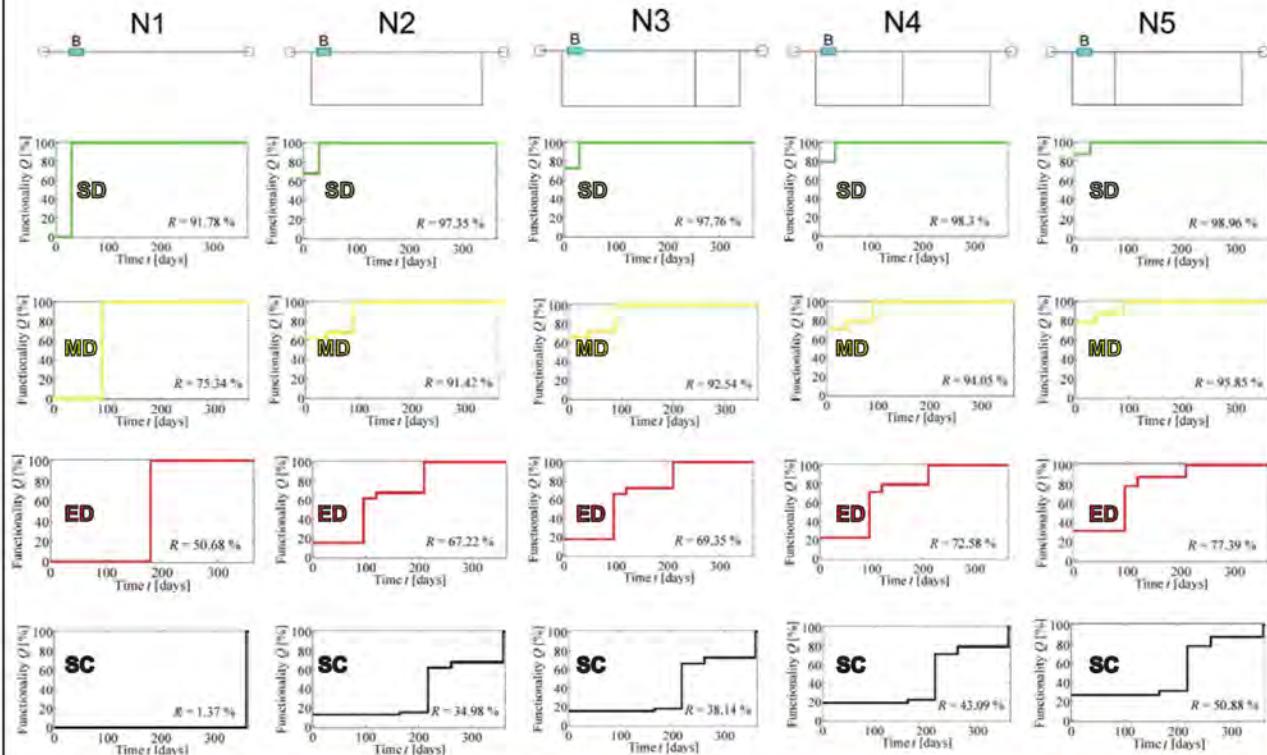
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Damage	$\omega$	$\rho$	$r_{DS,1}$	$r_{DS,2}$	$r_{DS,3}$	$r_{DS,4}$	$\delta_r$ [days]
SD	0.20	2.0	1.00	-	-	-	30
MD	0.40	3.0	0.50	1.00	-	-	90
ED	0.60	4.0	0.20	0.50	1.00	-	180
SC	0.80	5.0	0.05	0.20	0.50	1.00	360



# Network Functionality and Resilience

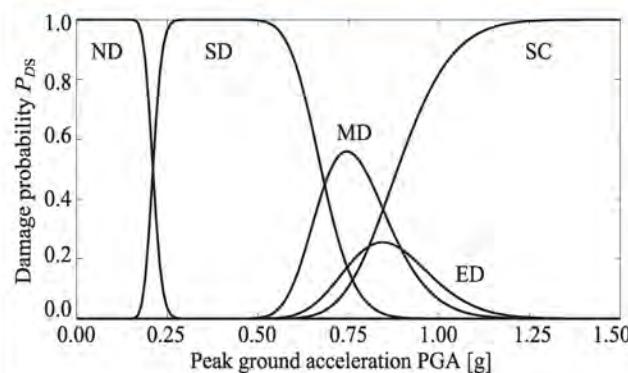
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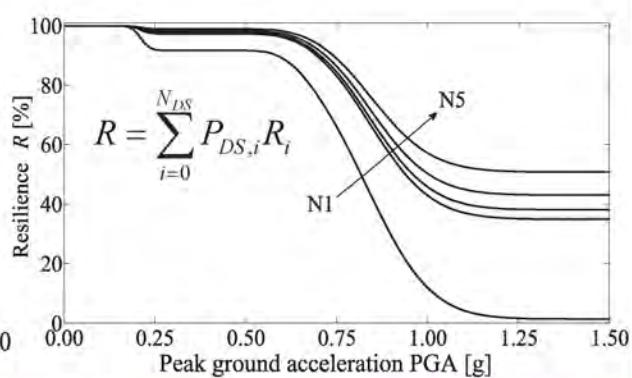
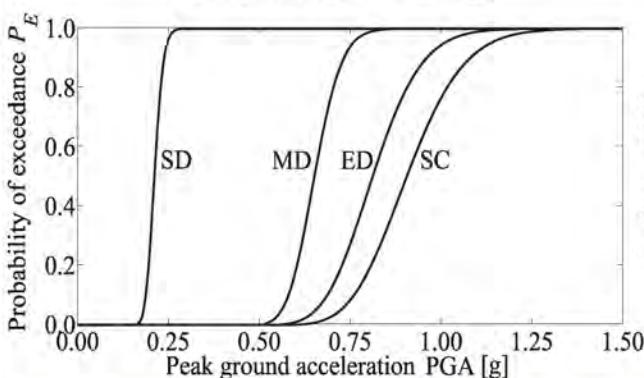
## Network Seismic Resilience ( $t_0=0$ )

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### Damage Probabilities

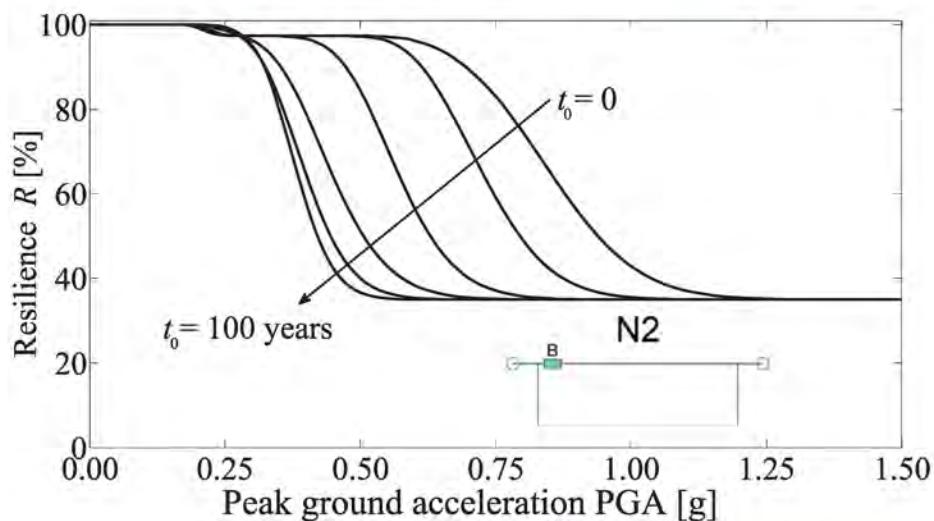
$$\begin{cases} P_{SC,4} = P_{E,4}(IM) \\ P_{ED,3} = P_{E,3}(IM) - P_{E,4}(IM) \\ P_{MD,2} = P_{E,2}(IM) - P_{E,3}(IM) \\ P_{SD,1} = P_{E,1}(IM) - P_{E,2}(IM) \\ P_{NC,0} = 1 - P_{E,1}(IM) \end{cases}$$



## Time-Variant Seismic Resilience (N2)

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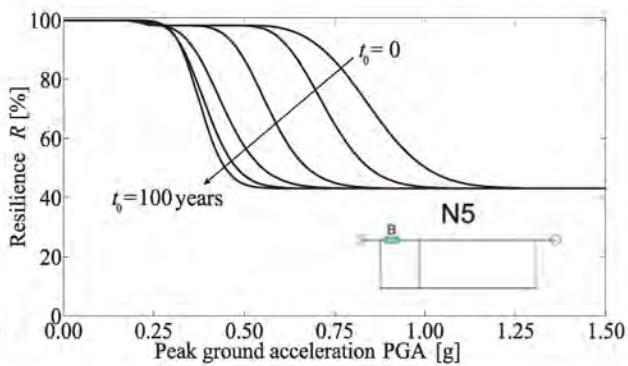
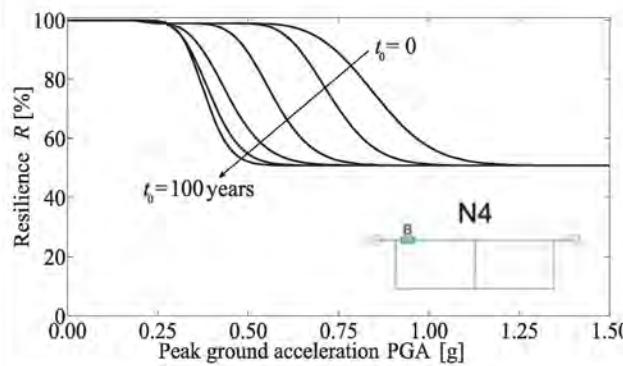
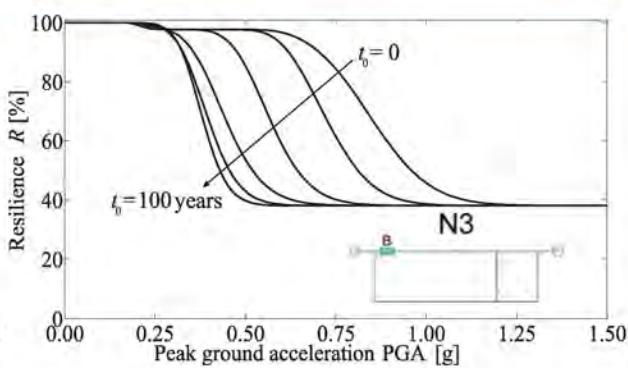
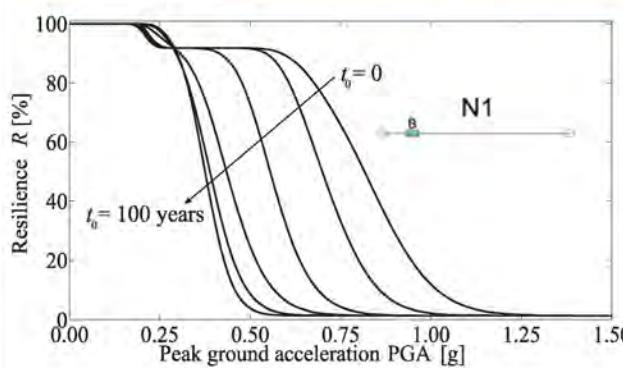
$$R(IM, t_0) = \sum_{i=0}^{N_{DS}} P_{DS,i}(IM, t_0) \cdot R_i$$





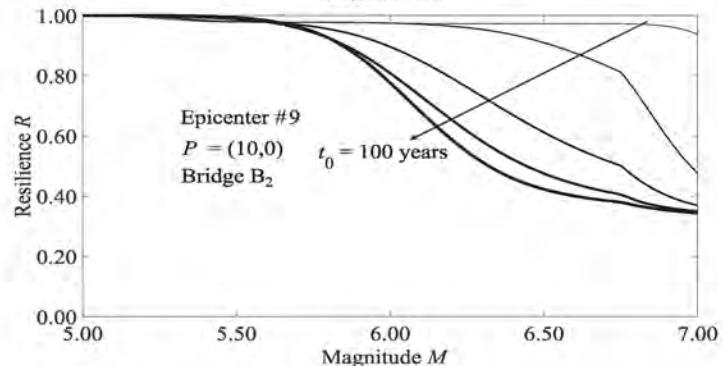
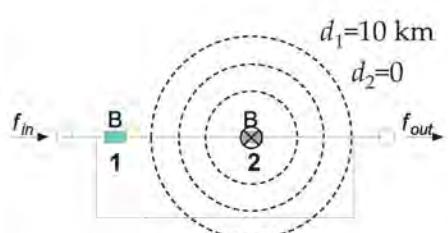
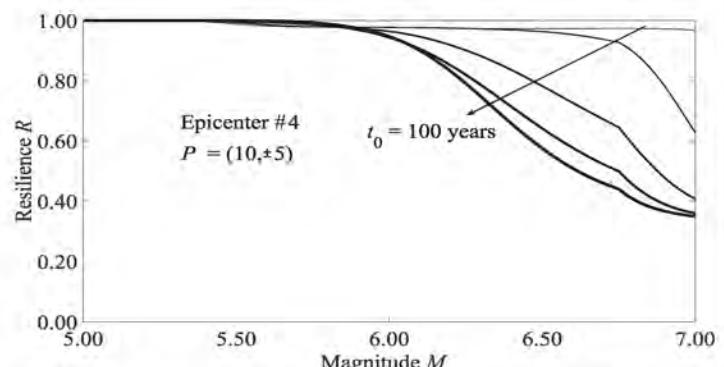
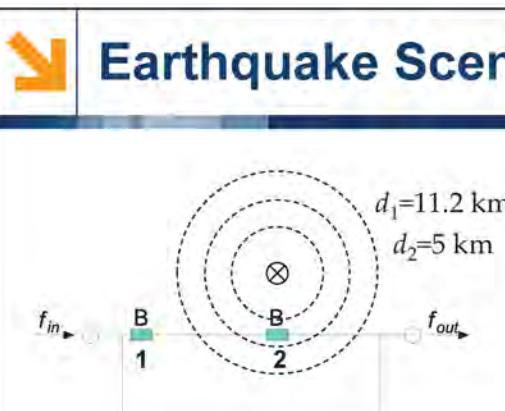
## Time-Variant Seismic Resilience

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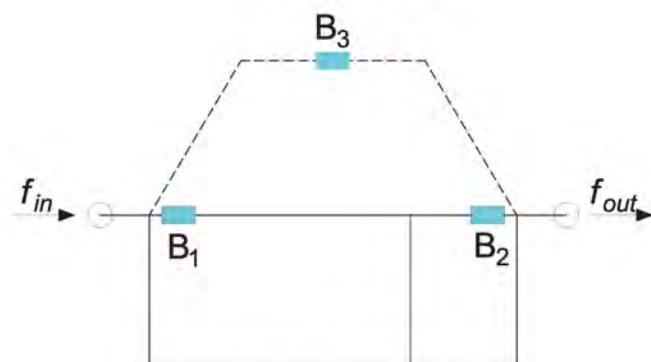


## Evolving Road Networks

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(a) Network N1

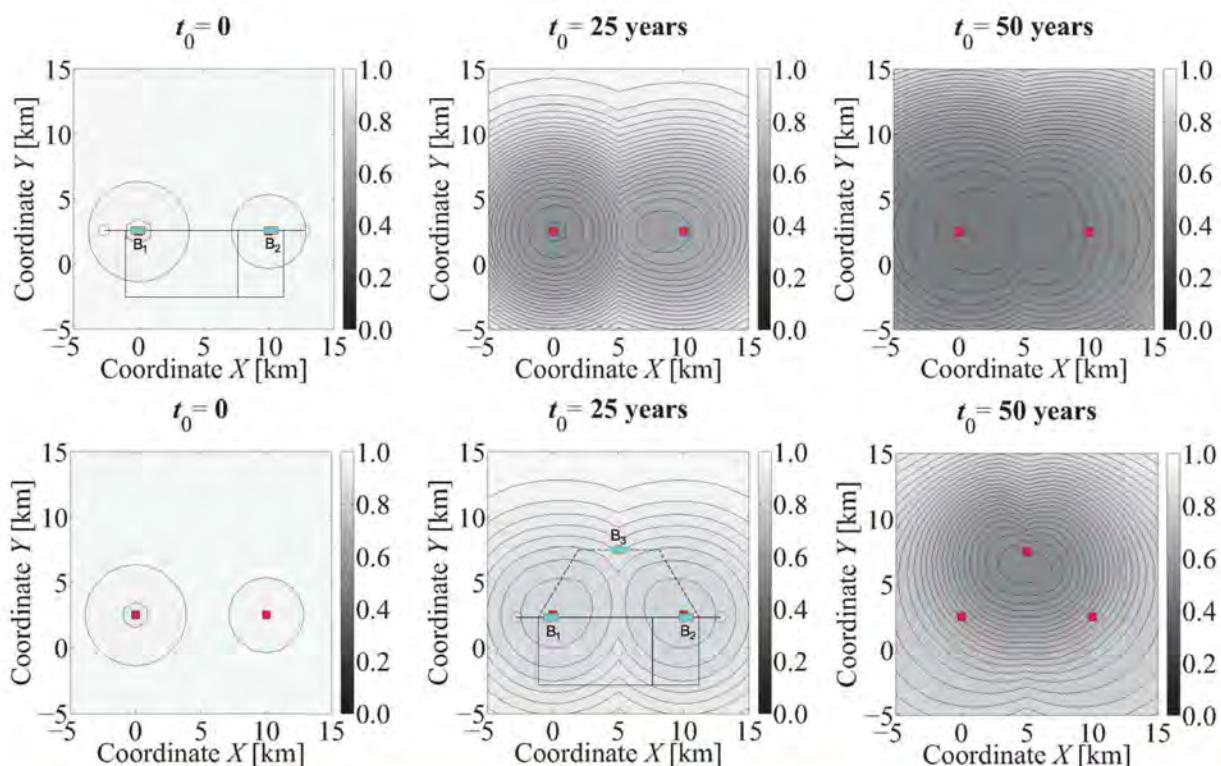


(b) Network N2



## Resilience Maps

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## Conclusions

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- The functionality and resilience of road networks can be substantially reduced due to seismic damage if traffic flows cannot be detoured to secondary roads (*detours in combination with re-entry links mitigate the loss of functionality and, consequently, make road networks more resilient with respect to seismic events*).
- Structural deterioration reduces over time the seismic capacity of bridges. Therefore, the combined effects of seismic and environmental hazards make **seismic resilience depending on the time of occurrence of the seismic event**.
- The impact of the environmental exposure depends on the earthquake scenario and related seismic exposure of the most important bridges in the network. The effects of deterioration can be reduced by road network upgrading.
- The results show the importance of a **multi-hazard life-cycle oriented approach to seismic design of resilient structures and infrastructures** considering the **network upgrading** to limit the effects of aging and deterioration and establish effective and rapid post-event recovery procedures.

