

# Task D

## Real-time monitoring during a seismic sequence

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# Objectives of the task

- Methodology for the assessment of time-variant seismic risk of single structures over short time-scales (i.e., during the seismic crisis)
- Algorithms for the implementation of the fully-automatic system for the building tagging
- Algorithms for early warning systems accounting for cumulative damage during seismic sequences
- Installation of sensing units for building monitoring.

## Partners in charge

AMRA - GFZ

## Deliverable

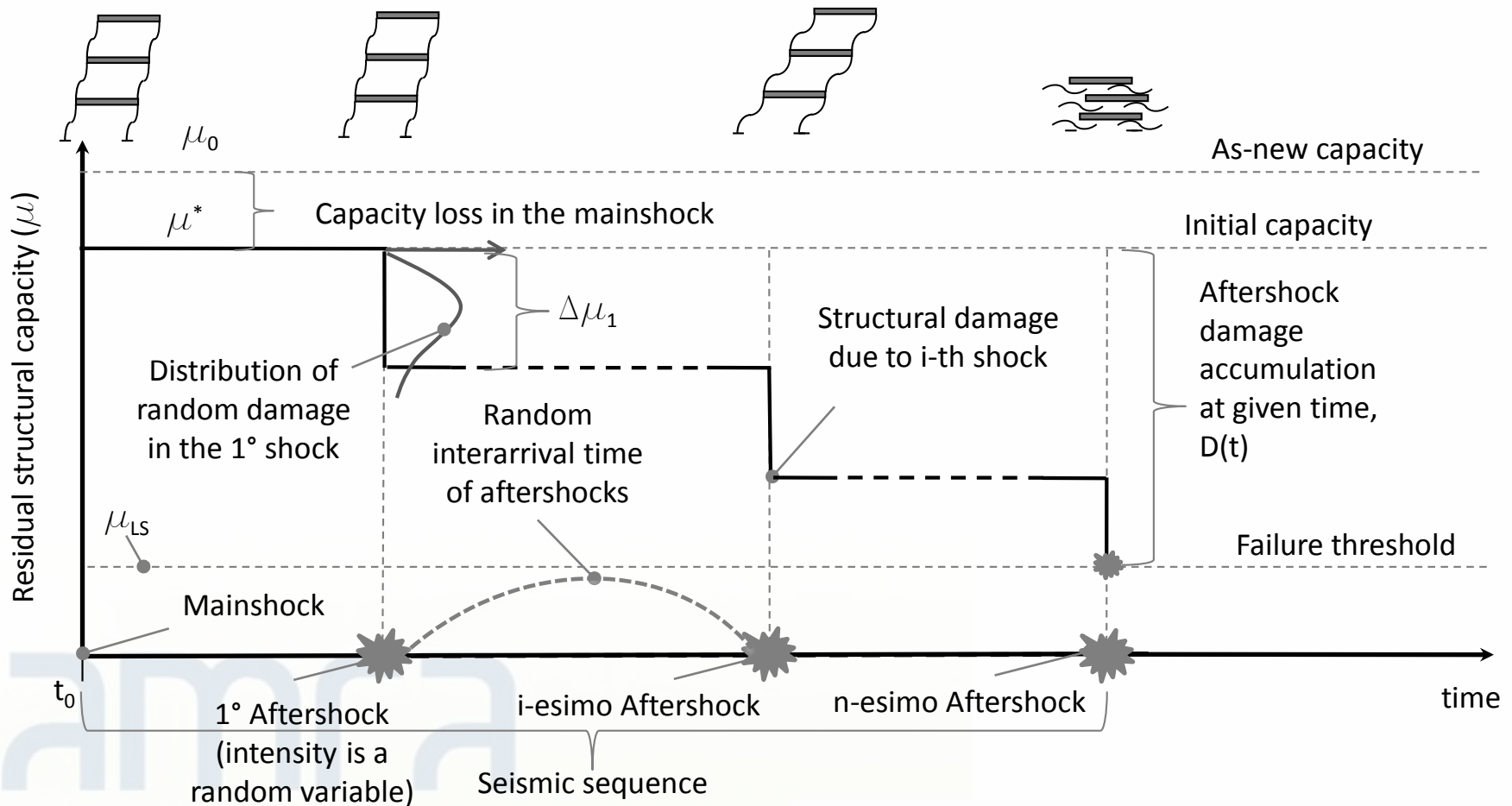
- Guidelines for the assessment of time-variant seismic risk of monitored single structures (12/2016)

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# Time-dependency in seismic risk

Damage accumulation for a mainshock-damaged structure in an aftershock sequence.



$$\mu(t) = \mu^* - D(t) = \mu^* - \sum_{i=1}^{N(t)} \Delta\mu_i \quad P_f(t) = 1 - R(t) = P[\mu(t) \leq \mu_{LS}] = P[D(t) \geq \mu^* - \mu_{LS}] = P[D(t) \geq \bar{\mu}]$$

# Aftershock probabilistic seismic hazard assessment

Daily rate of aftershocks' occurrence for non-homogenous Poisson process:

$$\lambda(t) = \left( 10^{a+b \cdot (m_m - m_l)} - 10^a \right) / (t+c)^p$$

Modified Omori law

Gutenberg-Richter coefficients

Magnitude range

Time since the mainshock

Expected number of aftershocks in the  $(t, t+\Delta t)$  interval:

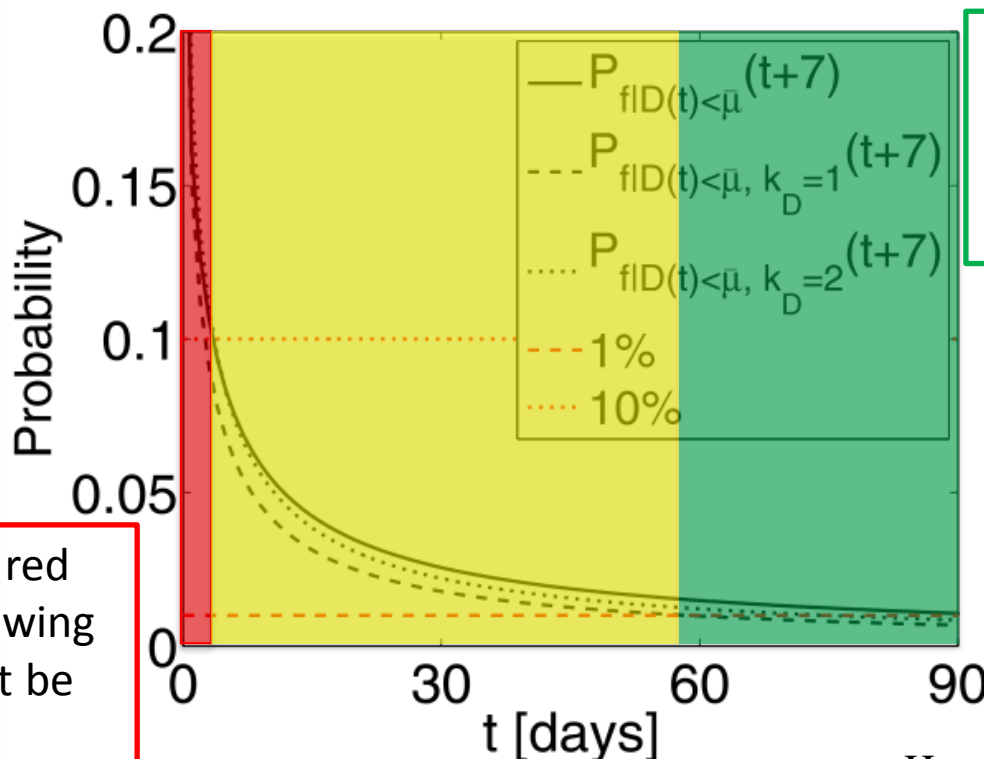
$$E[N(t, t+\Delta t)] = \int_t^{t+\Delta t} \lambda(\tau) \cdot d\tau = \frac{10^{a+b \cdot (m_m - m_l)} - 10^a}{p-1} \cdot \left[ (t+c)^{1-p} - (t+\Delta t+c)^{1-p} \right]$$

APSHA *filters* the rate by the (time-invariant) probability that the ground motion intensity measure,  $IM$ , at the site of interest exceeds a threshold:

$$\lambda_D(t) = \lambda(t) \cdot P[IM > im^*] = \lambda(t) \cdot \iint_{m, r_s} P[IM > im^* | m, r_s] \cdot f_{M, R_s}(m, r_s) \cdot dm \cdot dr_s$$

Joint pdf of magnitude and source-to-site distance

# Non-evolutionary SDoF: Illustrative application



The structures is green tagged in the following week: i.e., ordinary activities can start.



The structures is red tagged in the following week: i.e., cannot be accessed.



The structures is yellow tagged in the following week: i.e., can be entered only by trained agents.



Hypotheses:

- ✓ Damages in different earthquakes are independent RVs
- ✓ Damage in the generic earthquake has always the same distribution marginal with respect to IM

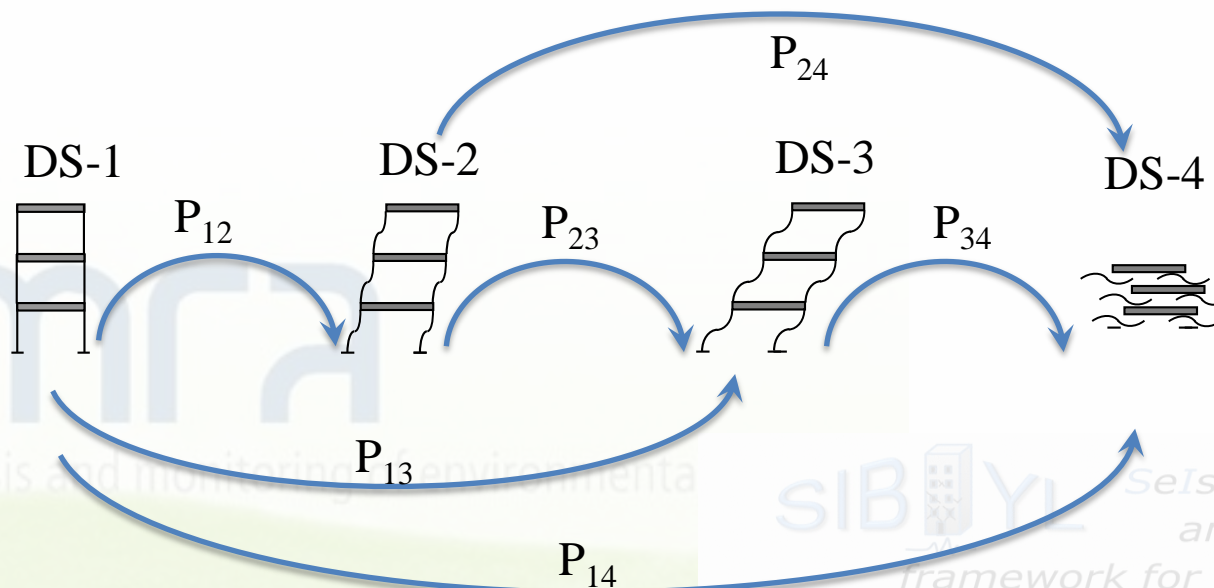
# Evolutionary SDoF and history-dependent damage measures

Earthquake damage is instantaneous with respect to the lifespan of the structure

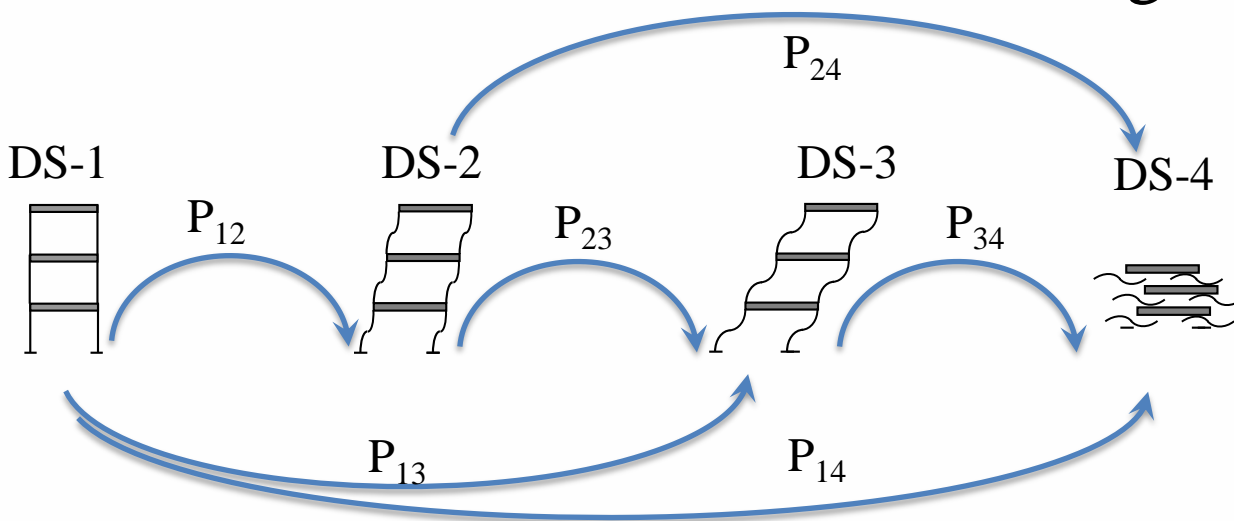
Damage distribution is dependent on the state of the structure at the time of each seismic shock

Structural conditions can be discretized in a finite number of damage states

Earthquake damage accumulation can be modelled via a Markov chain



# Seismic Damage



$$P_{ij|E} = \int_{im} \underbrace{P[j\text{-th state} | i\text{-th state} \cap IM = z]}_{\text{State-dependent fragility}} \cdot \underbrace{f_{IM|E}(z)}_{\text{Hazard at the site (IM independent and identically distributed random variable in different earthquakes)}} \cdot dz$$

State-dependent fragility

Hazard at the site  
(IM independent and identically distributed random variable in different earthquakes)

$$[P_E] = \begin{bmatrix} 1 - \sum_{j=2}^4 P_{1j} & P_{12} & P_{13} & P_{14} \\ 0 & 1 - \sum_{j=3}^4 P_{2j} & P_{23} & P_{24} \\ 0 & 0 & 1 - P_{34} & P_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

# Seismic Damage due to Aftershock

If the unit-time, rate of occurrence of earthquake shocks is small enough such that the probability of observing more than one seismic event in the unitary time interval is negligible:

$$P[j\text{-th state} | i\text{-th state}] = P_{ij} = v(t)_{E|m_A} \cdot P_{ij|E}$$

Rate of aftershock occurrence

The matrix reporting the probabilities of the structure moving between any two states in a unit-time interval:

$$[P(t, t + \Delta t)] = v(t)_{E|m_A} \cdot [P_E] + (1 - v(t)_{E|m_A}) \cdot [I] = [P]$$

Earthquake occurrence in the unitary time interval

No Earthquake in the unitary time interval

Certitude that the structure remains in the same state if no earthquakes occur.

Because the transition matrix changes with time leading to a non-homogenous Markov chain, the probabilistic prediction of the evolution of damage is:

$$[P(t, t + m)] = \prod_{i=1}^m [P(t + i - 1, t + i)]$$

# Seismic Damage due to Mainshock

If the unit-time, rate of occurrence of earthquake shocks is small enough such that the probability of observing more than one seismic event in the unitary time interval is negligible:

$$P[j\text{-th state} | i\text{-th state}] = P_{ij} = \nu_E \cdot P_{ij|E}$$

↓  
Rate of earthquake occurrence (HPP)

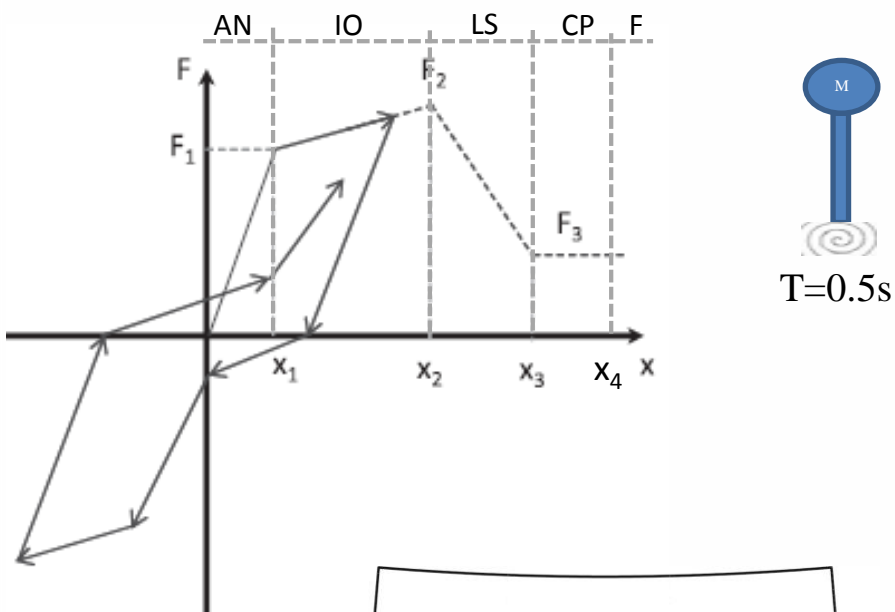
The matrix reporting the probabilities of the structure moving between any two states in a unit-time interval:

$$[P(t, t + \Delta t)] = \nu_E \cdot [P_E] + (1 - \nu_E) \cdot [I] = [P]$$

In  $m$  time intervals, exponentiation of the matrix provides new probabilities:

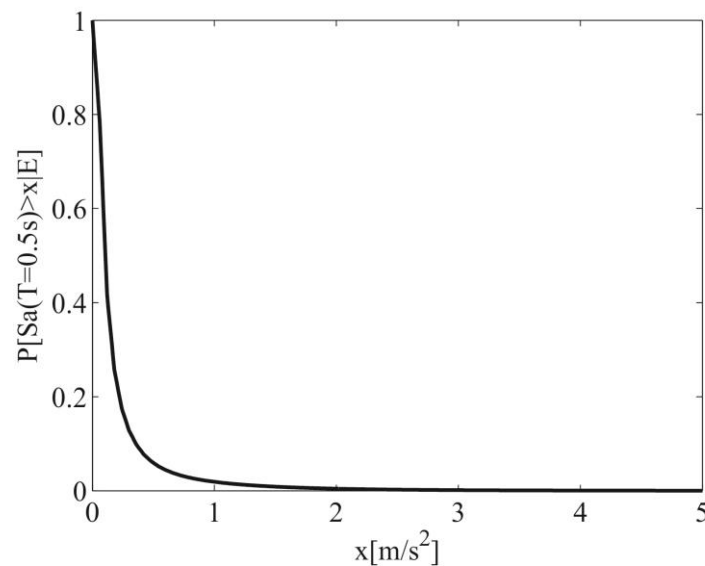
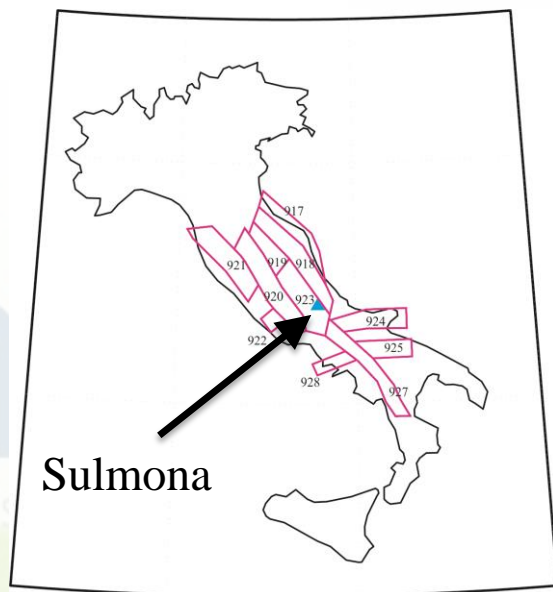
$$[P(t, t + m)] = [\nu_E \cdot [P_E] + (1 - \nu_E) \cdot [I]]^m = [P]^m$$

# Illustrative Application



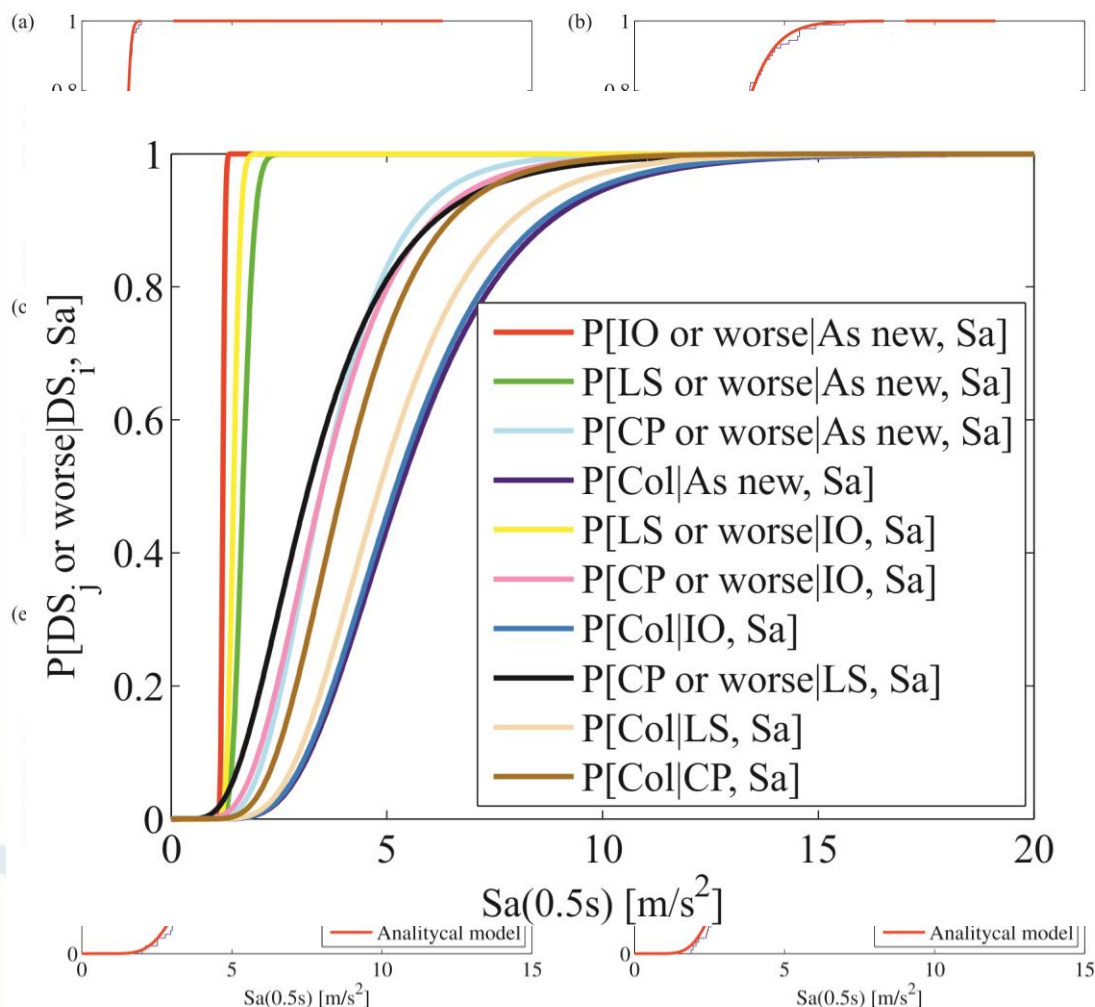
*displacement-related* damage index: the structure reaches collapse because it exceeds its maximum plastic displacement, that is maximum strain, independently of the amount of dissipated energy;

AN( $x_1$ )	IO( $x_2$ )	LS( $x_3$ )	CP( $x_4$ )	F
0.0076	0.0175	0.0497	0.1	-



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# Illustrative Application



Luco, N., Bazzurro, P., and Cornell, C.A. (2004). Dynamic versus static computation of the residual capacity of a mainshock-damaged building to withstand an aftershock, *13 WCEE*, Vancouver, Canada.

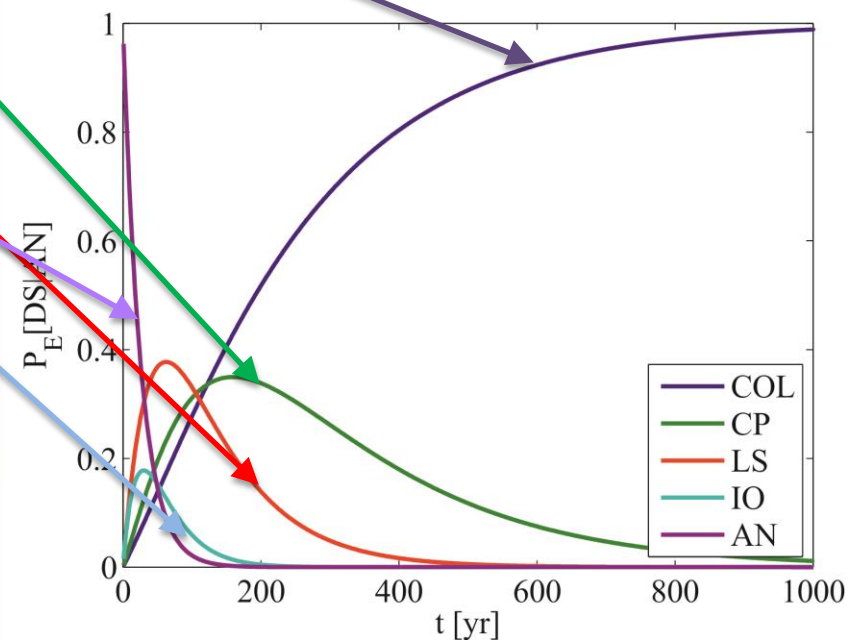
Iervolino, I., Giorgio, M., Chioccarelli, E. (2015). Markovian modelling of seismic damage accumulation, *Earthquake Engineering and Structural Dynamics*, 2015, doi: 10.1002/eqe.2668.

# Illustrative Application

## MAINSHOCK

Matrix reporting the probabilities of the structure moving between any two states in  $m$  time intervals:

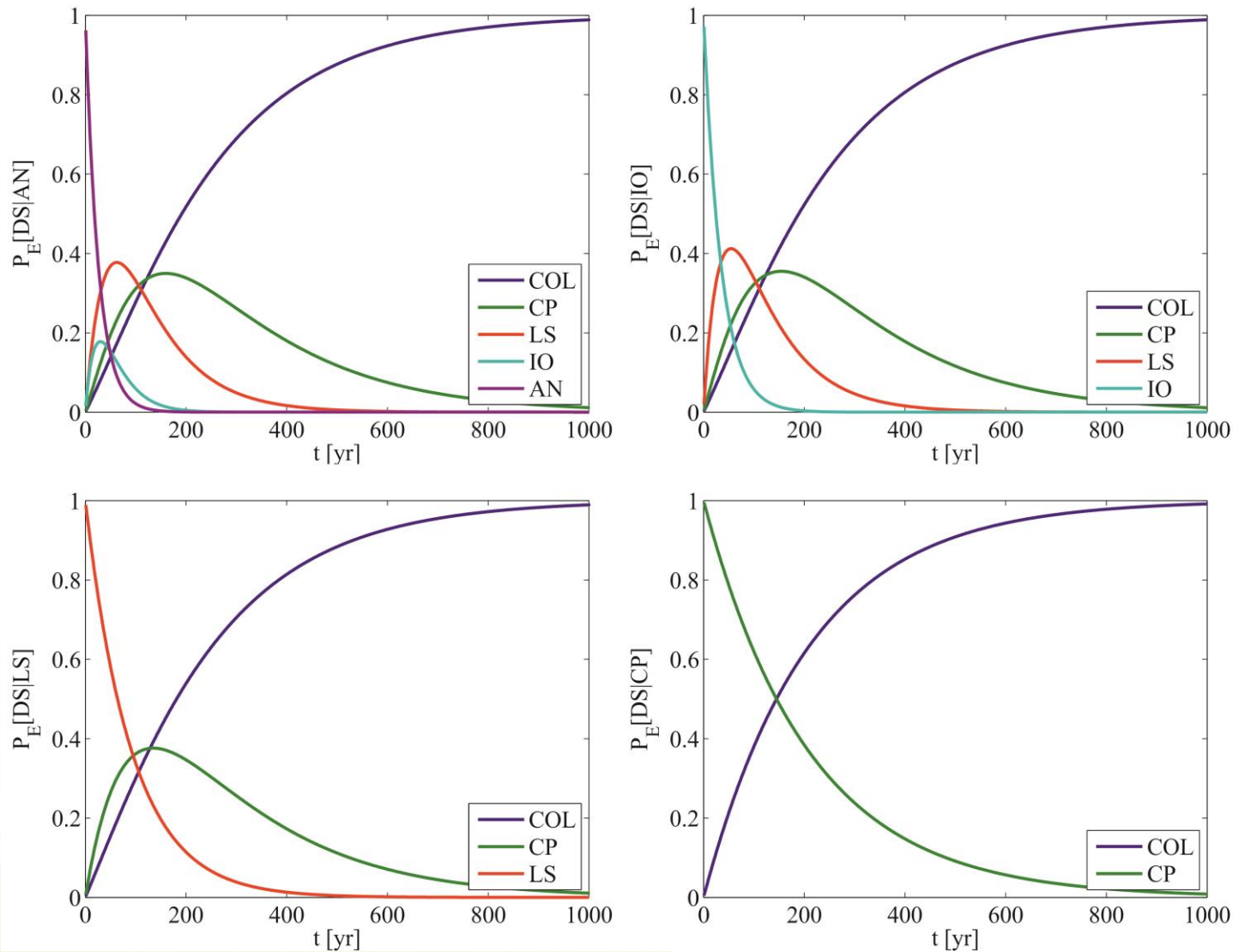
$$[P]^m = \begin{bmatrix} [P]_{11}^m & [P]_{12}^m & [P]_{13}^m & [P]_{14}^m & [P]_{15}^m \\ 0 & [P]_{22}^m & [P]_{23}^m & [P]_{24}^m & [P]_{25}^m \\ 0 & 0 & [P]_{33}^m & [P]_{34}^m & [P]_{35}^m \\ 0 & 0 & 0 & [P]_{44}^m & [P]_{45}^m \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



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# Illustrative Application

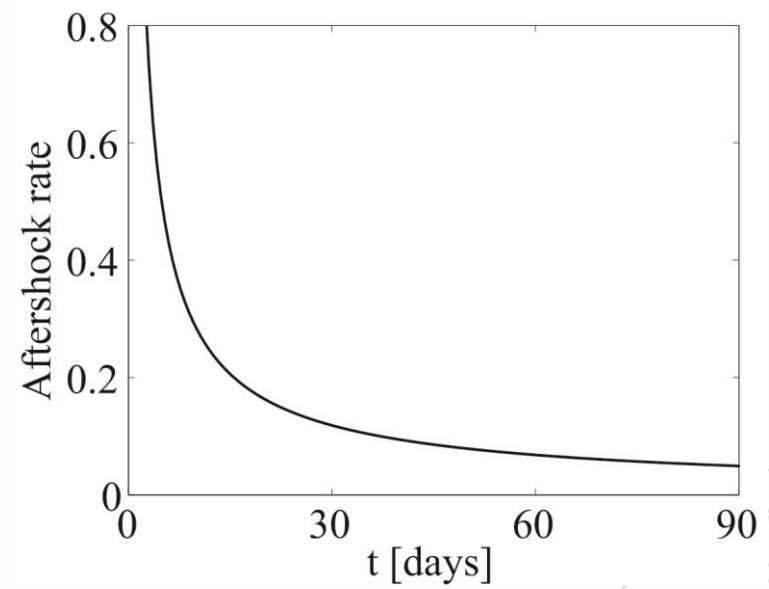
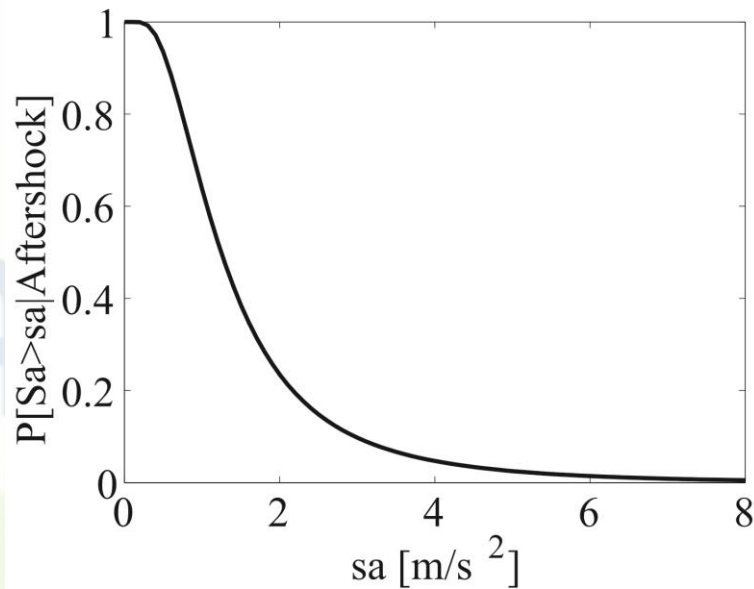
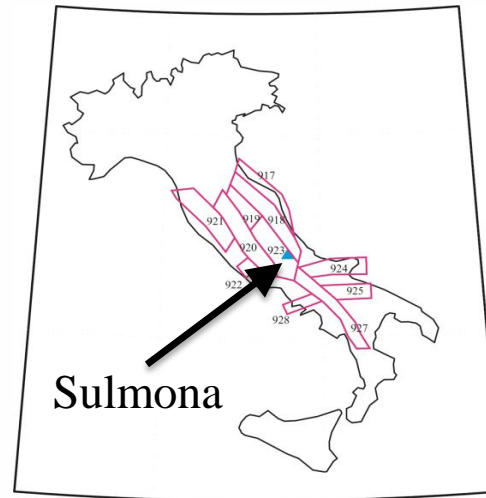
## MAINSHOCK



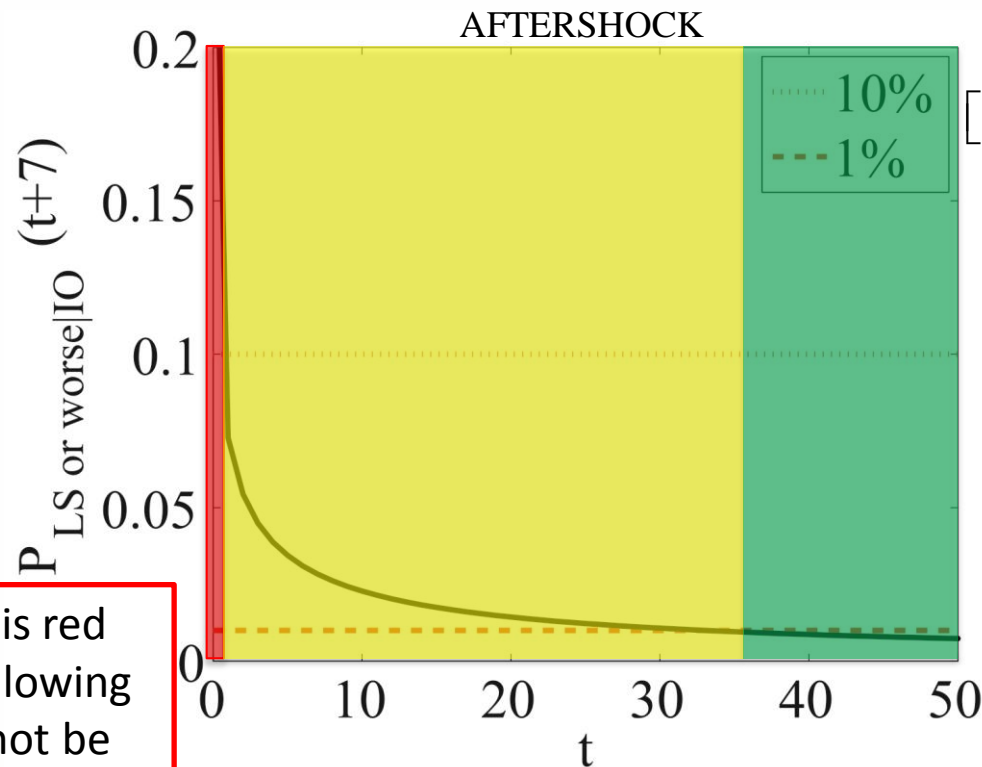
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 Protection

# Illustrative Application

AFTERSHOCK



# Illustrative Application



$$[P(t, t+m)] = \prod_{i=1}^m [P(t+i-1, t+i)]$$

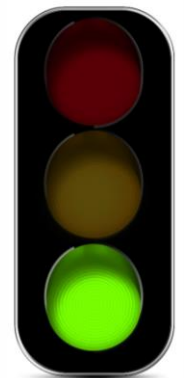
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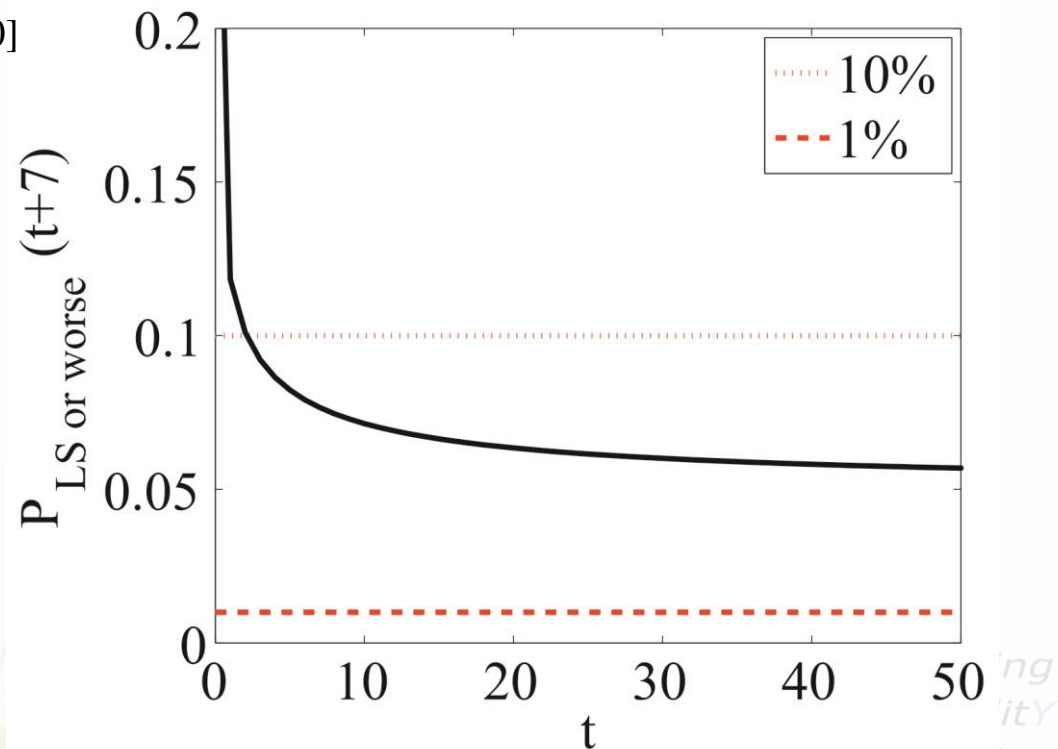
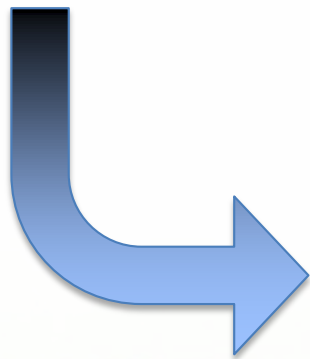
# Illustrative Application

## AFTERSHOCK

After the mainshock, the damage state of the structure may be unknown and a vector collecting the initial probabilities of structure being in one of the states can be used as shown:

$$\begin{bmatrix} P_{AN}^t & P_{IO}^t & P_{LS}^t & P_{CP}^t & P_F^t \end{bmatrix} \cdot \prod_{i=1}^m [P(t+i-1, t+i)] = \begin{bmatrix} P_{AN}(t, t+m) & P_{IO}(t, t+m) & P_{LS}(t, t+m) & P_{CP}(t, t+m) & P_F(t, t+m) \end{bmatrix}$$

$$\begin{bmatrix} P_{AN}^t & P_{IO}^t & P_{LS}^t & P_{CP}^t & P_F^t \end{bmatrix} = [0.05 \quad 0.90 \quad 0.05 \quad 0 \quad 0]$$



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# Conclusions

Two alternative models for the assessment of the seismic reliability of single structures have been developed.

Both models require an equivalent SDoF system representative of the protected structure and in both cases, an algorithm for automatic building tagging can be developed and integrated in the monitoring system.

Model 1 – Gamma distribution		Model 2 – Markovian chain	
Pros	Cons	Pros	Cons
	Suitable for structures with non-evolutionary behavior	Suitable for any kind of structure for which state-dependent fragility curves can be derived	
It refers to a simple SDoF system easy to be calibrated			Calibration may be time-consuming
	The chosen damage index can not be history-dependent	Any kind of damage index can be used	
Closed-form results	...but results depend only on two parameters	It uses simple matrix computations	The number and the characteristic of each damage states have to be carefully discussed

*Thank you for your kind attention*

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