Towards understanding and quantifying the value the value of SHM and inspection data for seismic risk management of buildings

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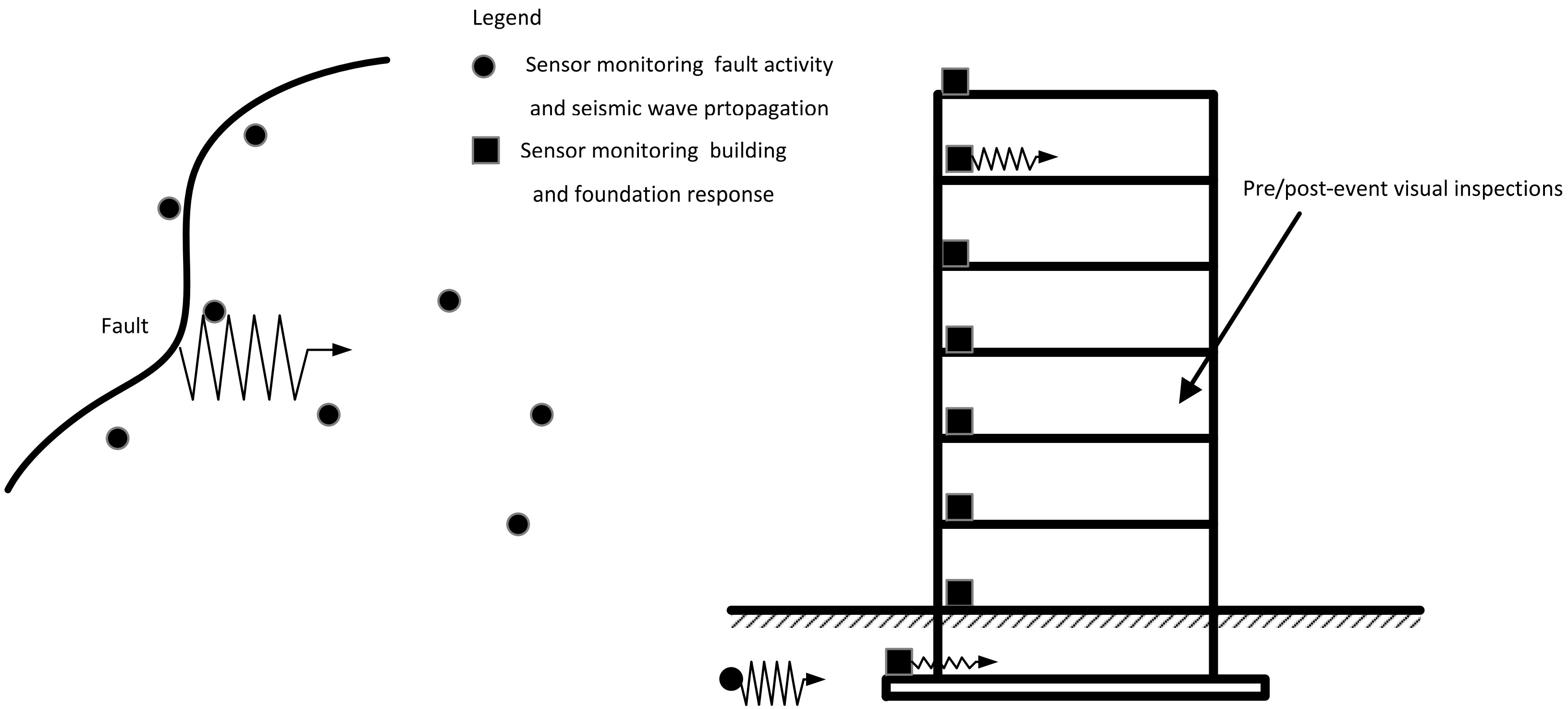
COST TU1402: Quantifying the Value of Structural Health Monitoring, Barcelona, 14-15 March 2016

Outline

- Introduction: Two types of seismic structural health monitoring
- Pre-posterior, risk-based decision-making framework for adoption of seismic monitoring
- Damage detection techniques in the probabilistic pre-posterior framework
- Utilizing both inspection and monitoring data
- Modelling of consequences and costs for seismic risk quantification for making decision about adoption of seismic monitoring
- Conclusions

Introduction:
Two types of seismic structural health monitoring

Seismic monitoring arrays



- Sensors on the building, foundations, and in close proximity of the structure
- Wide-area seismic arrays to monitor faults, wave propagation and attenuation

Two types of seismic SHM

Type 1: Quick post-event actual damage detection

- Depending on the output from the monitoring system the building will be either:
  - Evacuated, OR
  - Normal, uninterrupted building usage will quickly resume

- The different scenarios entail different consequences:
  - Evacuating when there has not been damage entails losses due to unnecessary business interruption, loss of rent income, cost of alternative accommodation etc.
  - Not evacuating when there has actually been damage entails the risk of further casualties, damage to content etc. due to aftershocks

Two types of seismic SHM

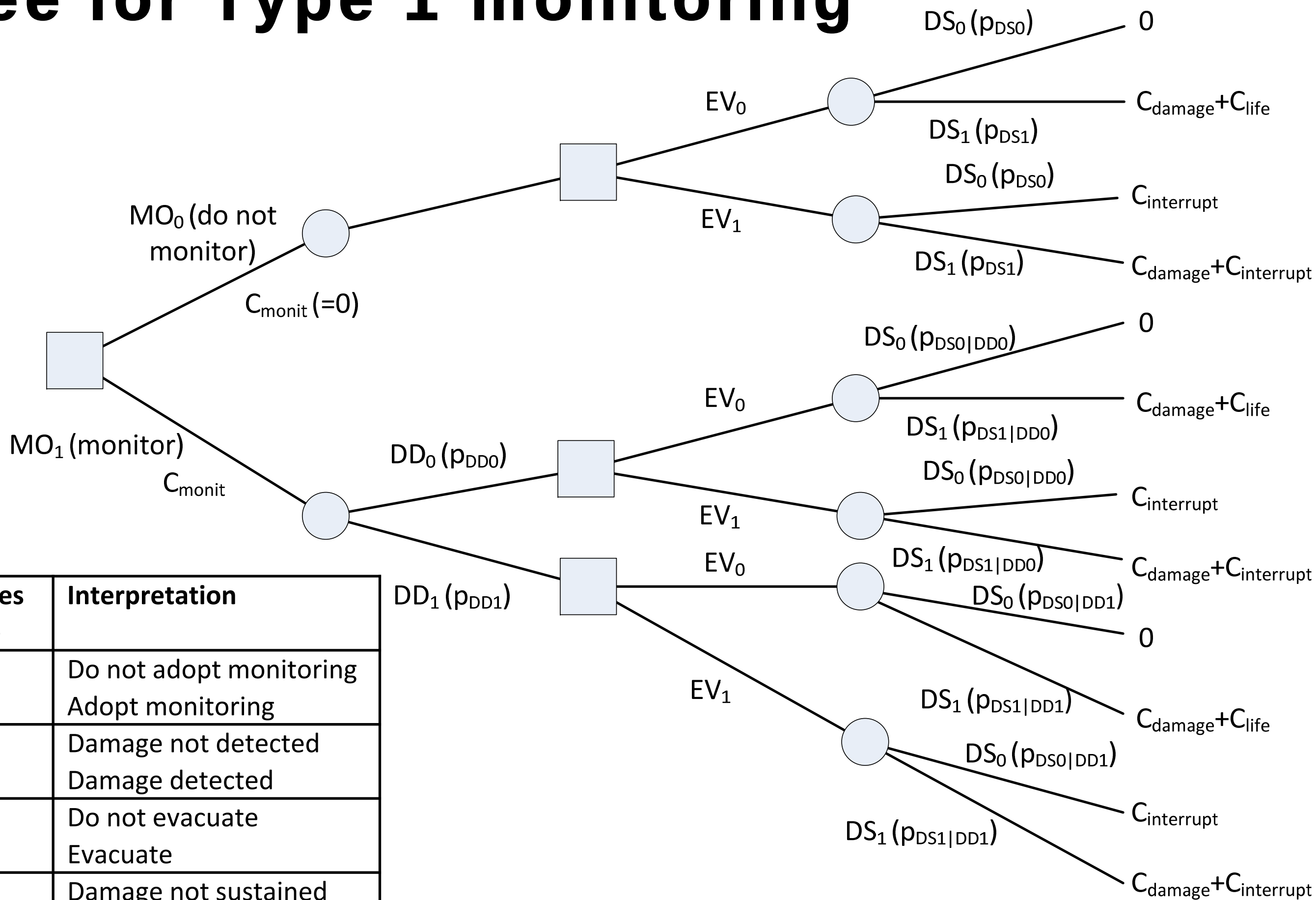
Type 2: Collection of data for updating hazard and vulnerability models

- Monitoring seismic faults and wave propagation, typically over extended periods of time to capture larger numbers and ranges of seismic events, to update probabilistic hazard models

- Monitoring of the building, typically over extended periods of time to capture larger numbers and ranges of responses to seismic events, to update probabilistic vulnerability models

Pre-posterior, risk-based decision-making framework for adoption of seismic monitoring

Decision tree for Type 1 monitoring



Decision/chance outcome	**Options/outcomes /states of nature**	**Interpretation**
Adopt monitoring system, **MO**	MO_0 MO_1	Do not adopt monitoring Adopt monitoring
Damage detected, **DD**	DD_0 DD_1	Damage not detected Damage detected
Evacuate building, **EV**	EV_0 EV_1	Do not evacuate Evacuate
Damage actually sustained, **DS**	DS_0 DS_1	Damage not sustained Damage sustained

Cost type	Symbol
Cost of monitoring system	C_{monit}
Cost of damage, casualties/injuries amongst occupants sustained immediately as the result of the main shock	C_{damage}
Cost of casualties/injuries amongst people who stay in the building following a decision not to evacuate if the building fails in an aftershock	C_{life}
Cost of interruption to business/occupancy following a decision to evacuate	$C_{interrupt}$

Pre-posterior analysis for Type 1 monitoring

Inputs:

- Prior probabilities of damage occurrence $\mathbf{p}_{\mathbf{DS1}}$ & $\mathbf{p}_{\mathbf{DS0}}$ from seismic risk analysis (hazard exposure and vulnerability)
- Likelihoods of damage detection (true/false/positives/negatives) from laboratory experimentation and numerical studies of the performance of damage detection system

	DD_0	DD_1
DS_0	$\mathbf{p}_{\mathbf{DD0}\mid\mathbf{DS0}}$	$\mathbf{p}_{\mathbf{DD1}\mid\mathbf{DS0}}$
DS_1	$\mathbf{p}_{\mathbf{DD0}\mid\mathbf{DS1}}$	$\mathbf{p}_{\mathbf{DS1}\mid\mathbf{DS1}}$

Outputs:

- Posterior probabilities of damage being present given it has been indicated by monitoring system from Bayesian analysis
- Posterior probabilities of damage being indicated by monitoring system from Bayesian analysis

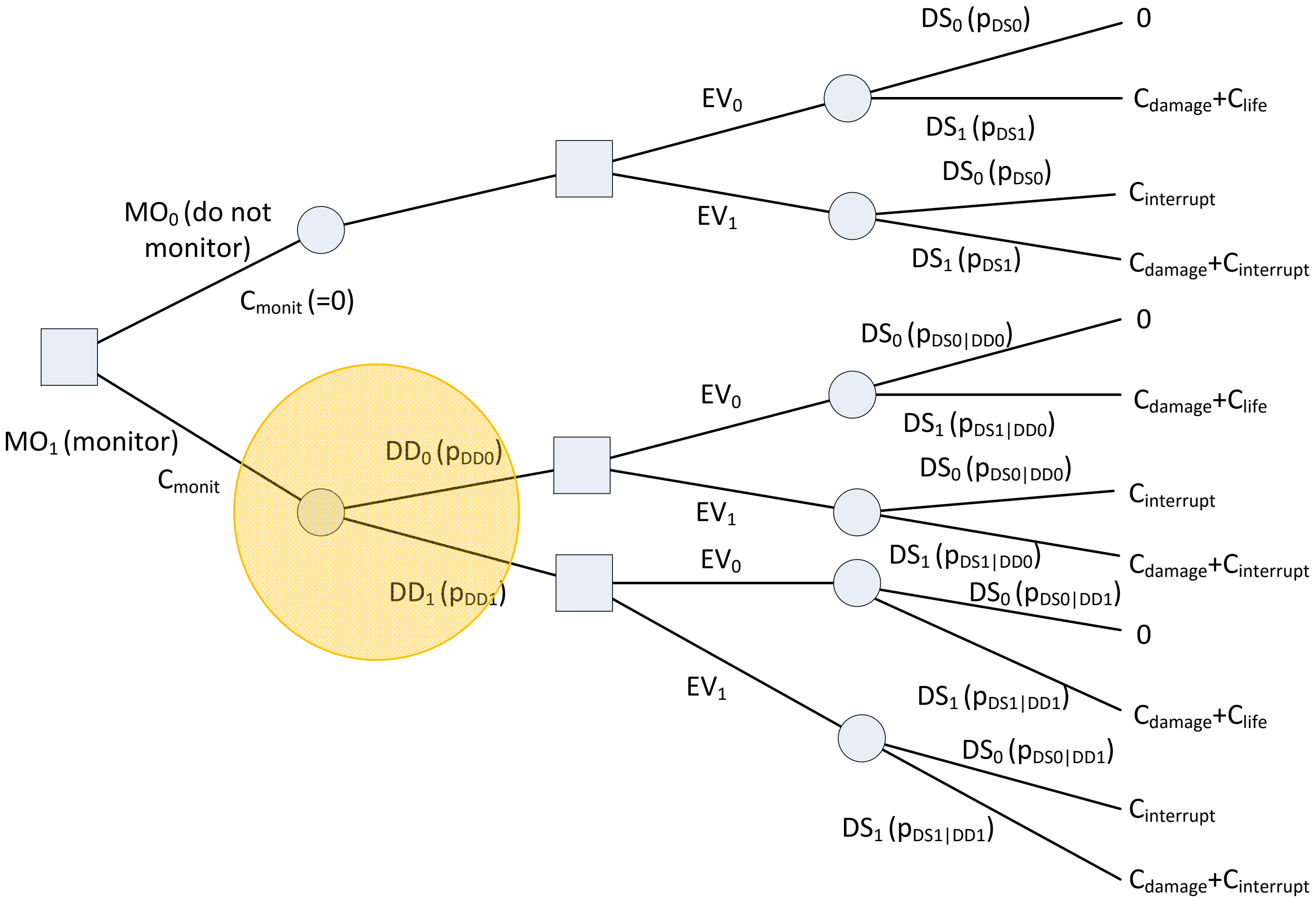
State of nature	Prior probabilities	Likelihoods	Intersection probability	Posterior probability
DS_0	p_{DS0}	$p_{DD0\mid DS0}$	$p_{DS0}\ p_{DD0\mid DS0}$	$\mathbf{p}_{\mathbf{DS0}\mid\mathbf{DD0}}= p_{DS0}\ p_{DD0\mid DS0}/\ p_{DD0}$
DS_1	p_{DS1}	$p_{DD0\mid DS1}$	$p_{DS1}\ p_{DD0\mid DS1}$	$\mathbf{p}_{\mathbf{DS1}\mid\mathbf{DD0}}= p_{DS1}\ p_{DD0\mid DS1}/\ p_{DD0}$
			$\mathbf{p}_{\mathbf{DD0}}= p_{DS0}\ p_{DD0\mid DS0}+p_{DS1}\ p_{DD0\mid DS1}$	
DS_0	p_{DS0}	$p_{DD1\mid DS0}$	$p_{DS0}\ p_{DD1\mid DS0}$	$\mathbf{p}_{\mathbf{DS0}\mid\mathbf{DD1}}= p_{DS0}\ p_{DD1\mid DS0}/\ p_{DD1}$
DS_1	p_{DS1}	$p_{DD1\mid DS1}$	$p_{DS1}\ p_{DD1\mid DS1}$	$\mathbf{p}_{\mathbf{DS1}\mid\mathbf{DD1}}= p_{DS1}\ p_{DD1\mid DS1}/\ p_{DD1}$
			$\mathbf{p}_{\mathbf{DD1}}= p_{DS0}\ p_{DD1\mid DS0}+p_{DS1}\ p_{DD1\mid DS1}$	

- Optimal decision that minimizes expected cost (risk) from decision tree via e.g. working backwards through the decision tree

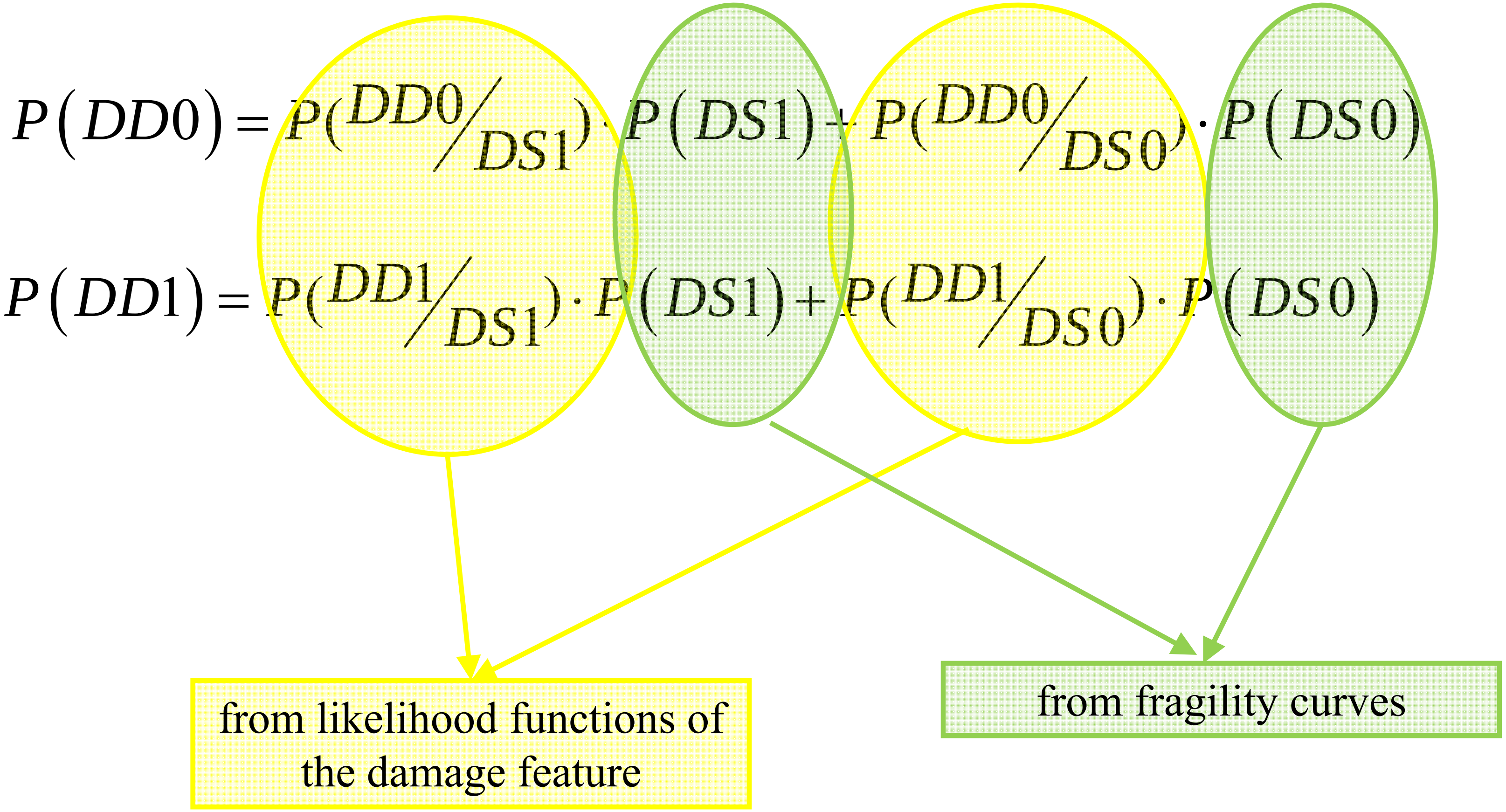
$$MO_{opt}=\min_{MO_i\in\mathbf{MO}} E_{DD}\min_{EV_k\in\mathbf{EV}} E_{DS|DD}\left[C\left(MO_i,DD_{j,}EV_{k,}DS_l\right)\right]$$

Damage detection techniques in the probabilistic pre-posterior framework

Probability of (no) detection



Probability of (no) detection



$$P\left(DD0\right)=P\left({}^{DD0}\!/_{DS1}\right)\cdot P\left(DS1\right)+P\left({}^{DD0}\!/_{DS0}\right)\cdot P\left(DS0\right)$$

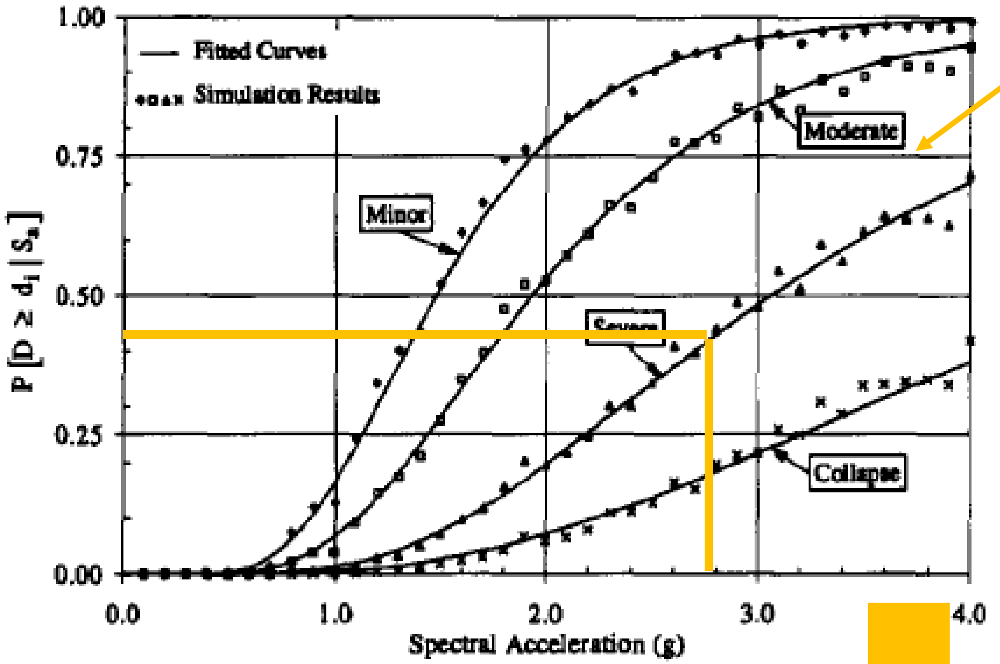
$$P\left(DD1\right)=P\left({}^{DD1}\!/_{DS1}\right)\cdot P\left(DS1\right)+P\left({}^{DD1}\!/_{DS0}\right)\cdot P\left(DS0\right)$$

from likelihood functions of the damage feature

from fragility curves

The fragility curves

Plot of the conditional probabilities of exceeding a given damage state (Ds_i) at various levels of ground motion (a_k)



i-th damage state

$$P(DS_{ik}) = P\left[D \geq d_i \middle| A = a_k \right]$$

Singhal A., KiremidjianAS (1996) A method for probabilistic evaluation of seismic structural damage. *J Struct Eng ASCE* 122(12):1459–1467

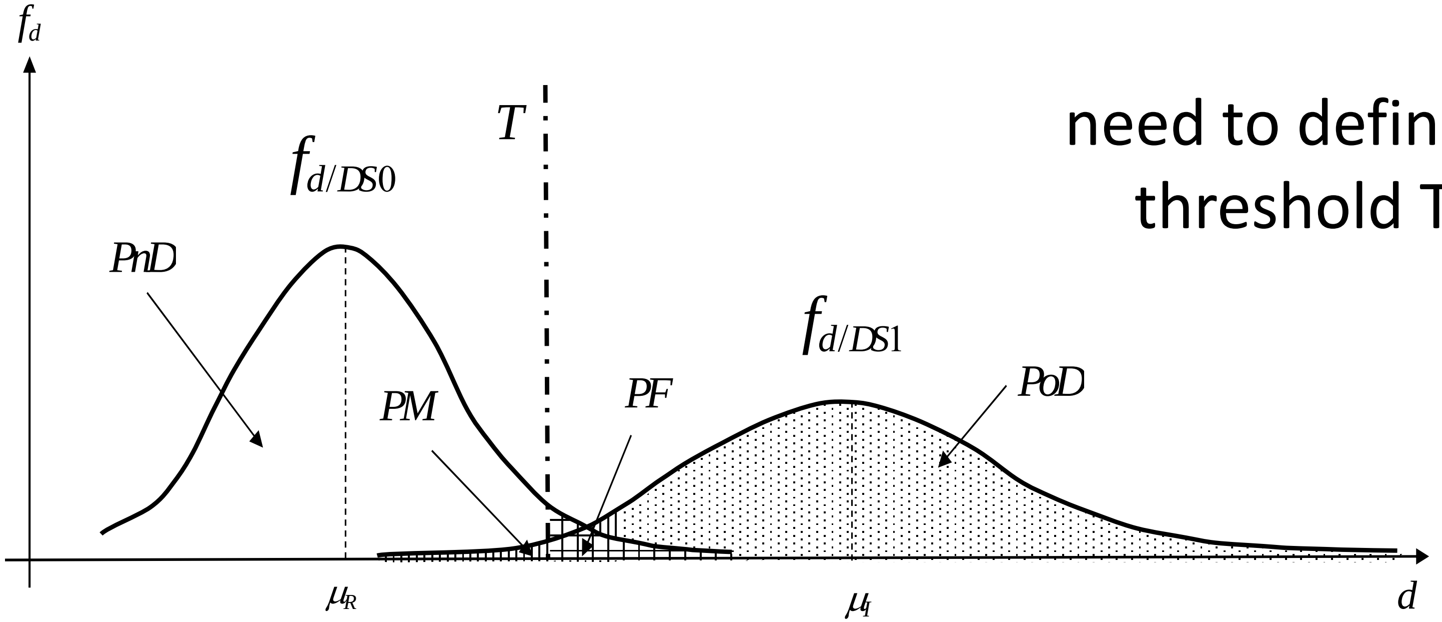
Prior probabilities $P(DS_i)$

The likelihood functions

In the framework of the quantification of the value of a monitoring system to be installed, the likelihood functions cannot be estimated on the structure to be monitored since the monitoring system is not yet installed.

Their estimation has to be carried out basing on numerical models or using statistical models of the distributions themselves which is a challenging task due to the difficulty in reliably simulating both the structural nonlinear behavior and the variability of the damage feature with the random sources.

Likelihood functions of the damage feature



need to define a threshold T

$P(DD0/DS0)$ **P**robability of **no** **D**etection (**PnD**)

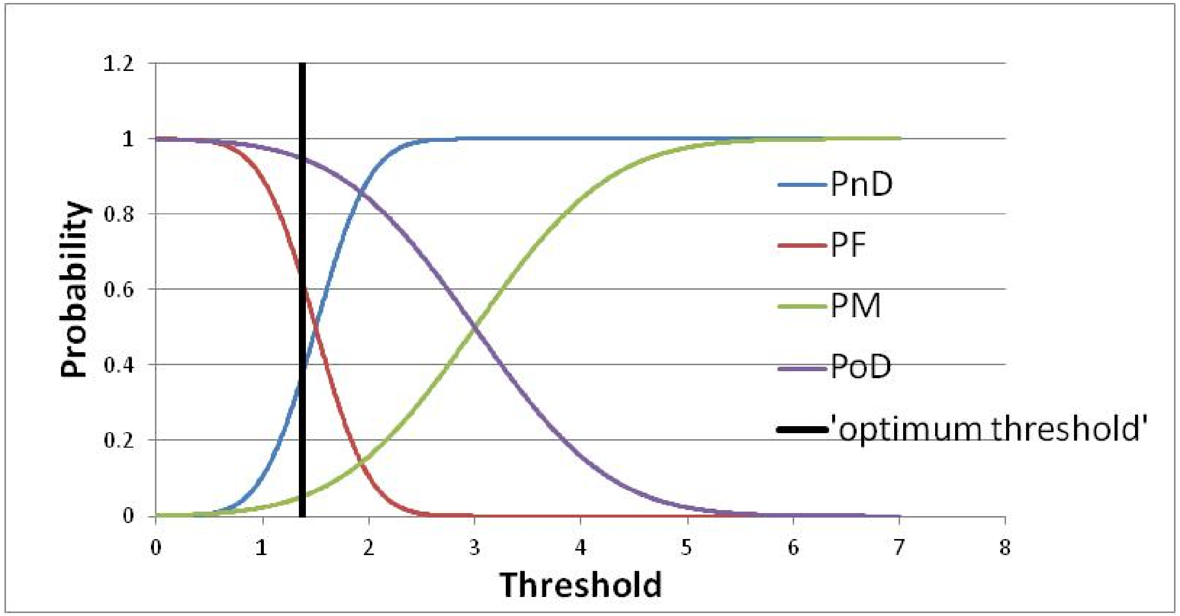
$P(DD1/DS0)$ **P**robability of **F**alse alarm (**PF**)

$P(DD0/DS1)$ **P**robability of **M**issing alarm (**PM**)

$P(DD1/DS1)$ **P**robability of **D**etection (**PoD**)

Example (ctd)

The conditional probabilities depend on the threshold T

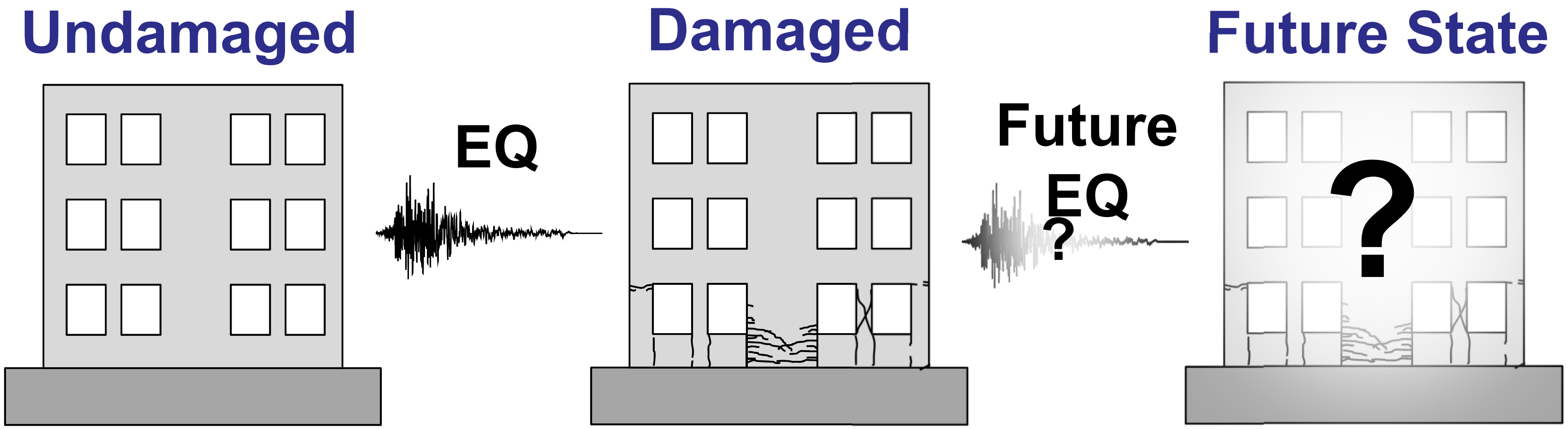


Choice of the threshold:
equal cost max consequences of PF and PM

$$PM \cdot \left(C_{damage} + C_{casualty} \right) = PF \cdot C_{interrupt}$$

Utilizing both inspection and monitoring data

Utilizing both inspection and monitoring data



Pre-Event Characteristics

Post-Event Characteristics

Post-EQ Risk

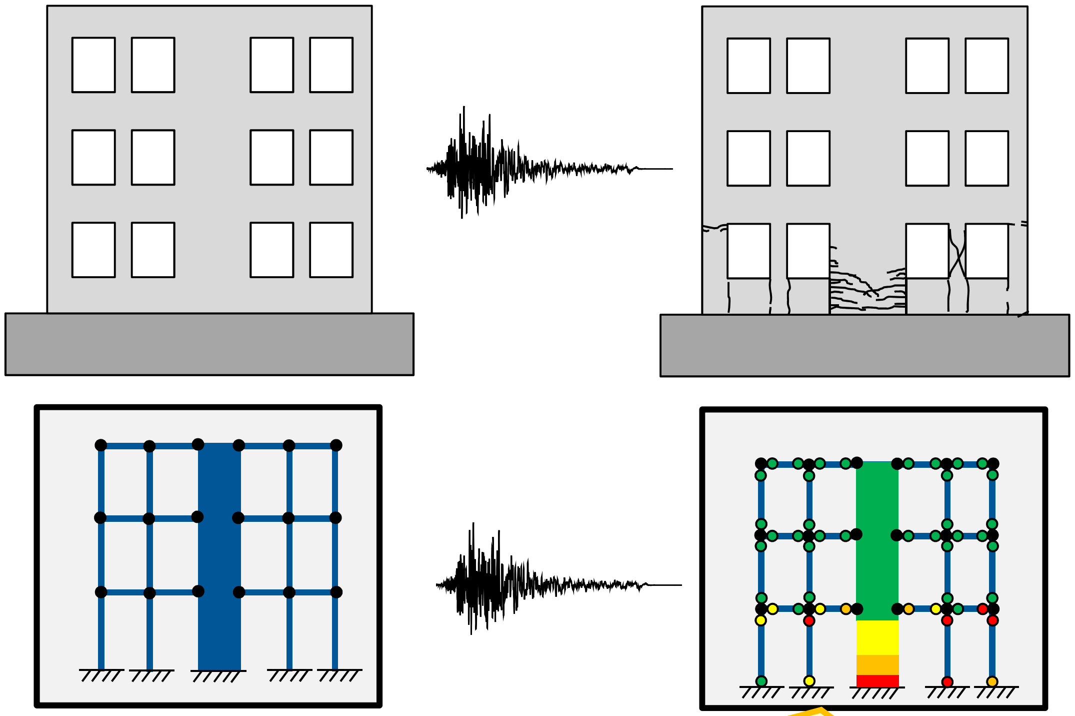
Hazard
Vulnerability
Consequences

Stiffness
Damping
Strength
Ultimate limit state
etc.

Observed or estimated parameters

Estimated parameters

Utilizing both inspection and monitoring data



Undamaged

Damaged

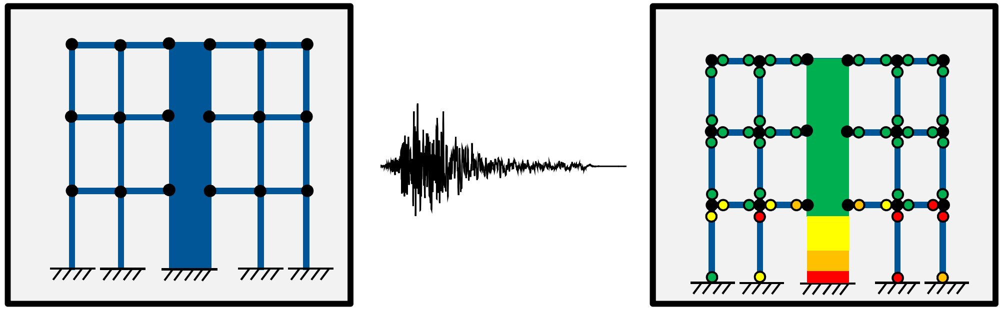
Actual Building

Analysis Model

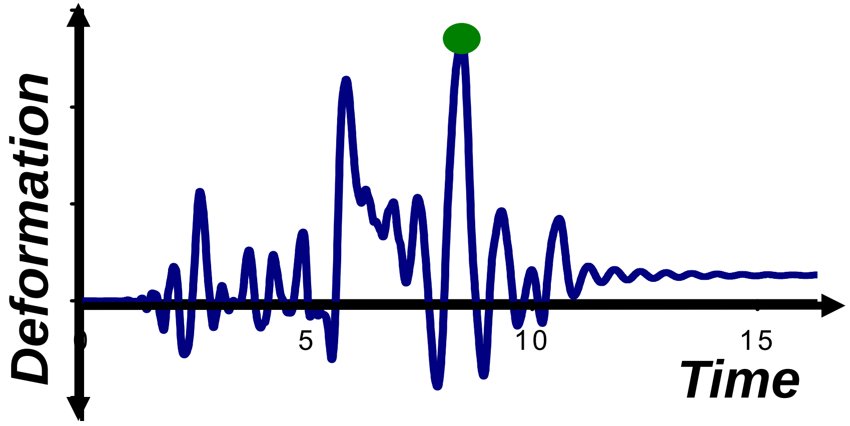
New
Stiffness
Damping
Strength
etc.

An "accurate" model should provide results that are in agreement with actual damage

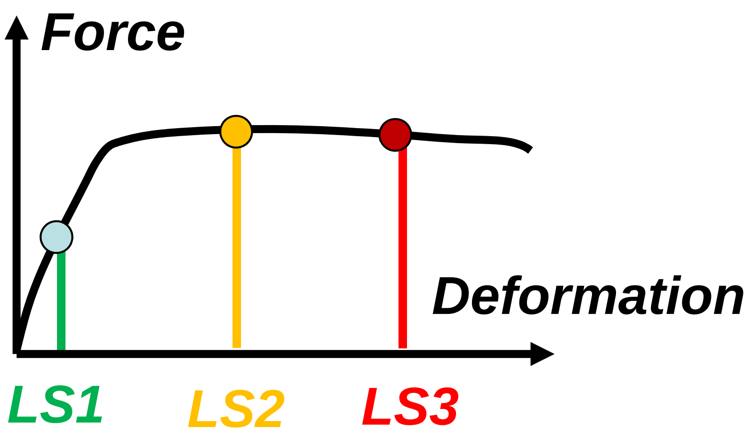
Utilizing both inspection and monitoring data



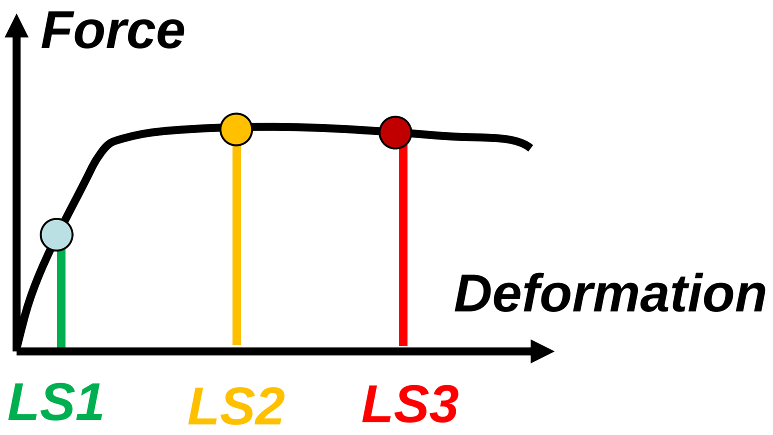
Response Simulation



Limit State Estimation



Utilizing both inspection and monitoring data



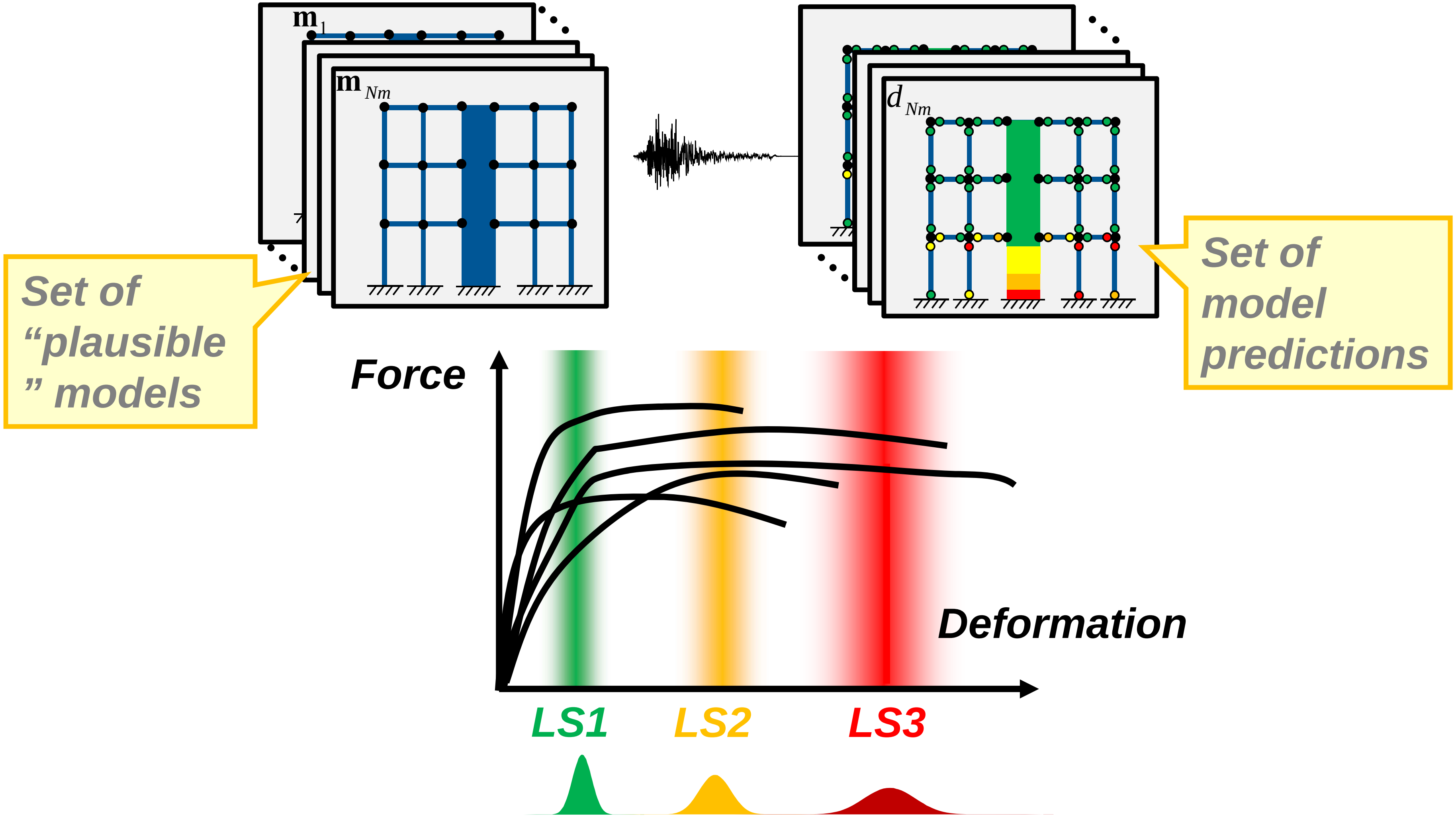
Example:
RC Members

Cover Concrete Spalling

Concrete Cracking

Reinforcement buckling

Utilizing both inspection and monitoring data

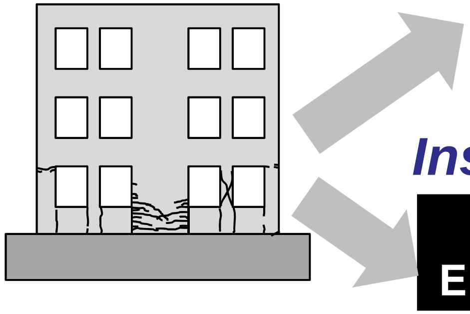


Set of “plausible” models

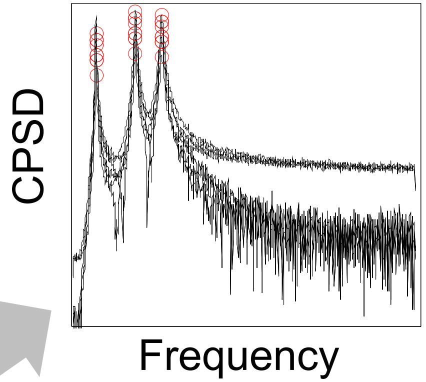
Set of model predictions

Utilizing both inspection and monitoring data

Damaged Structure



Monitoring Data

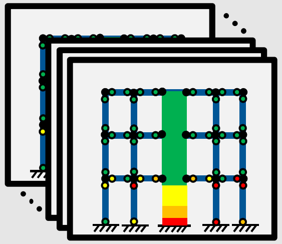


Period
Damping
Mode shapes
etc.

Inspection Data

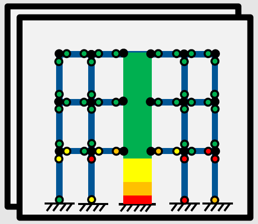
Element	Damage Mechanism	Damage Severity
1	Flexural	High
2	Shear	Low
3	Axial	Moderate
:	:	
N_e	-	None

All Models



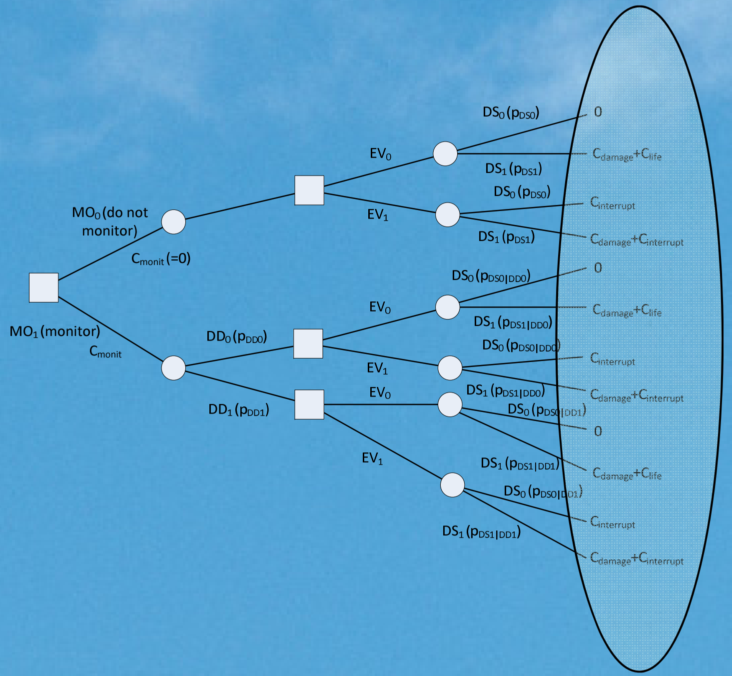
Evaluating the Posterior Likelihoods

Best Models



Post-EQ Risk Assessment

Consequence and cost modelling



Classification of consequences / costs

- Immediate consequences (cannot be avoided using monitoring)

vs.

- Delayed consequences (can be managed using monitoring)

(Similar to direct vs. indirect consequences used in robustness assessment but based on time scale)

Types of consequences

Type	**Immediate consequences**	**Delayed consequences**
Structure and content	Immediate damage to structure (repair or rebuild)	Damage to structure because it was not repaired and sustained further damage/collapsed in an aftershock(s)
	Immediate damage to non-structural components and services (repair or replace)	Damage to non-structural elements because structures was not repaired and sustained further damage/collapsed in an aftershock(s)
	Immediate damage to content and equipment (repair or replace)	Damage to content/equipment because structure was not repaired or content/equipment removed and sustained further damage in an aftershock(s)
Human	Immediate fatalities	Fatalities due to uninterrupted use of damaged structure which later collapses in an aftershock
	Immediate injuries	Injuries due to uninterrupted use of damaged structure which later collapses in an aftershock
	Immediate trauma	Trauma due to uninterrupted use of damaged structure which later collapses in an aftershock
Function	Loss of residence due to immediate damage	Additional loss of residence due to uninterrupted use of damaged structure which later collapses in an aftershock
	Business interruption due to immediate damage	Additional business interruption due to uninterrupted use of damaged structure which later collapses in an aftershock

Example on modelling consequences

Estimating numbers of fatalities N_f due to collapse

- Modification of a model by Coburn et al. (1992):

$$N_f = M_1 \times M_2 \times M_3 \times \left(M_4 + M_5\right)$$

- M_1 = maximum number of people in the building
- M_2 = occupancy ratio when earthquake hits (night/day; weekday/weekend)

Accurate data will be available from swipe/proximity card systems operating at entrances of office buildings etc.

- M_3 = ratio of occupants trapped in the building

$$M_3 = \frac{1}{M_1} \sum_{i=0}^{n} \gamma_i N_i \left(A_{col\%,i} \cup A_{col\%,i+1}\right)$$

n = number of floors

N_i = number of occupants on i-th floor

γ_i = number of occupants of i-th floor who are likely to escape (50% for ground floor for total collapse)

$(A_{col\%,i} \text{U} A_{col\%,i+1})$ = union of projected collapsed areas of i-th and (i+1)-th floor

- M_4 = ratio of those trapped killed immediately

Estimated as 0.4 for RC buildings

- M_5 = ratio of those trapped who will die later (not rescued on time)

Estimated as between 0.7 and 0.9 x(M_3–M_4) for RC buildings

Conclusions

- Two types of seismic SHM systems were proposed for i) damage detection immediately after an event, and ii) long term collection of data to calibrate hazard exposure and/or vulnerability
- A pre-posterior decision making framework was adopted for quantifying the expected contribution of an SHM system to seismic risk reduction before it is actually procured and installed
- In order to cast the use of damage detection techniques in the probabilistic pre-posterior framework, the likelihoods and total probabilities were defined with reference to a damage detecting feature
- Taking into account both the monitoring-based and the inspection-based data is expected to lead to more reliable post-earthquake risk evaluation compared to the case of relying on only one of these sources
- It is critical to properly represent the aleatory and the epistemic uncertainty associated with the estimated performance of the structure and take these into account appropriately in post-earthquake risk evaluation
- Next step will be considering a realistic case study

Acknowledgement

Piotr Omenzetter's work within the Lloyd's Register Foundation Centre for Safety and Reliability Engineering at the University of Aberdeen is supported by Lloyd's Register Foundation. The Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research.