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Design of fragility curves

to characterize the vulnerability of structures under seismic loading

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Context

Vulnerability of existing structures subject to external hazard

Shih-Kang Dam, Chi-Chi earthquake, 1999, Taiwan [Faccioli, 2008]

Church, L'Aquila earthaquake, 2009, Italy [Limoge, 2016]

Issues

- Structural safety
- Preservation of historical heritage

Need for a decision-support tool

Requirements

- Relate the hazard to its effects on structures
- Account for uncertainties (hazard, structural state)

→ Integration into a **probabilistic risk assessment approach**

Need for a decision-support tool

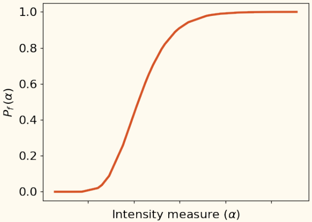
Introduction of fragility curves

Requirements

- Relate the hazard to its effects on structures
- Account for uncertainties (hazard, structural state)

$\rightarrow$ Integration into a **probabilistic risk assessment approach**

Fragility curve



Conditional failure probability $P_f(\alpha)$

(function of hazard intensity α)

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- More precision on fragility curves

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3 Application to a typology of masonry buildings

Fragility curves : definition

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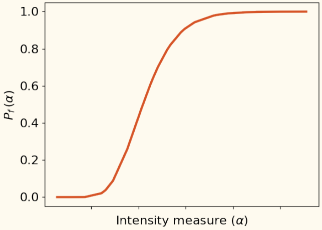
Probability that the damage measure exceeds a defined threshold, given a hazard intensity.



$$P_f(\alpha) = P\left(DS \geq ds_i \,/\alpha\right)$$

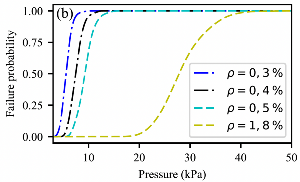
- DS : Damage State (damage indicator)
- ds_i : Pre-defined damage state threshold
- α : intensity measure

Applications

- Structures, components
- Stock of structures
- All kind of hazards

Examples

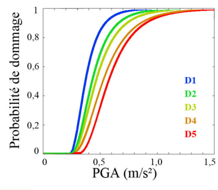
Fragility of a reinforced concrete wall subject to snow avalanches [Favier et al., 2018]

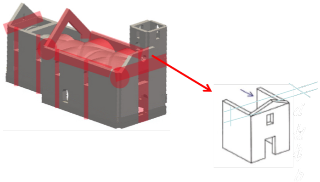


Influence of the reinforcement ratio ρ

- Damage indicator : ultimate displacement of the middle of the wall
- Intensity mesasure : maximal pressure applied by the avalanche to the wall over time.

Fragility of a chuch subject to seismic hazard [Limoge, 2016]





D_i : levels of damage thresholds

- Damage indicator : Overturning of the top front panel between nave and choir.
- Intensity mesasure : Peak ground acceleration (maximum acceleration of the seismic signal over time).

Probabilistic risk assessment

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$$P = \int_0^{\alpha_{\max}} -P_f(\alpha) \frac{dH(\alpha)}{d\alpha} d\alpha$$

P : total probability of damage or failure, function of :

Probabilistic risk assessment

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$$P = \int_0^{\alpha_{\text{max}}} -P_f(\alpha) \frac{dH(\alpha)}{d\alpha} d\alpha$$

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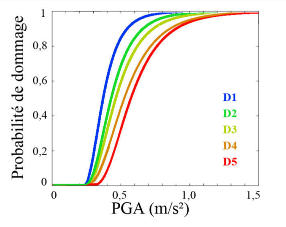
- $P_f(\alpha)$: probability of failure given a hazard intensity α.



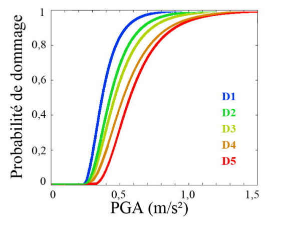
[Limoge, 2016]

Probabilistic risk assessment

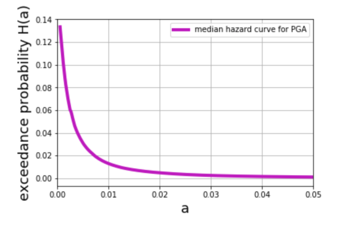
$$P = \int_0^{\alpha_{\max}} -P_f(\alpha) \frac{dH(\alpha)}{d\alpha} d\alpha$$

P : total probability of damage or failure, function of :

- $P_f(\alpha)$: probability of failure given a hazard intensity α.
- $H(\alpha)$: Hazard curve (probability of exceeding intensity α.)
  $-\frac{dH(\alpha)}{d\alpha}$: probability of occurrence of the intensity α.



[Limoge, 2016]



[Zentner, 2018, PIA SInaps@]

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Probabilistic risk assessment

$$P = \int_0^{\alpha_{\max}} -P_f(\alpha)\,\frac{dH(\alpha)}{d\alpha}\,d\alpha$$

P : total probability of damage or failure, function of :

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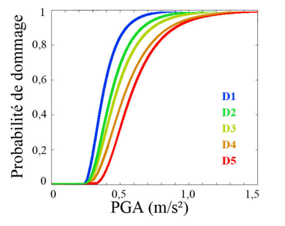
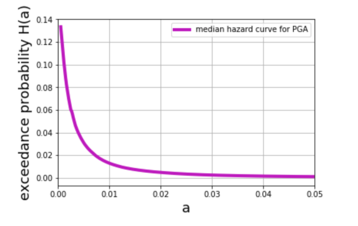
$\Rightarrow$ Sum over all the scenarii.



[Limoge, 2016]



[Zentner, 2018, PIA SInaps@]

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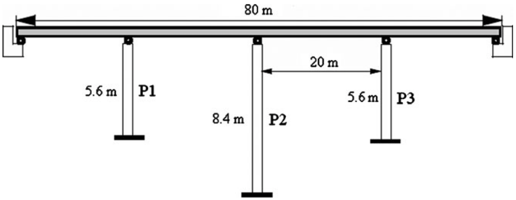
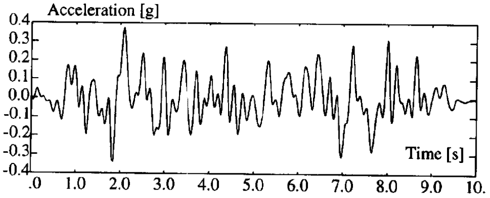
Model of structure : SDOF oscillator

Middle pier of a viaduct, pseudo-dynamically tested in Ispra (scale 1:2.5)

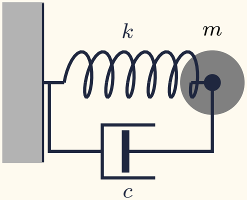


Model of the 1:2.5 scale structure
[Grange et al., 2010]



Seismic loading in the transverse direction
[Pinto et al., 1996]

▸ **Numerical model as a single degree of freedom (SDOF) oscillator**



$$m\,\ddot{u} + c\,\dot{u} + k = -m\,a_g$$

- k, m computed from the real scale structure, with a natural frequency $f_0 = 1.7\,Hz$
- $c = 2\,m\,w_0 \xi$, with ξ chosen to be $5\,\%$
- a_g : ground acceleration

Numerical solution

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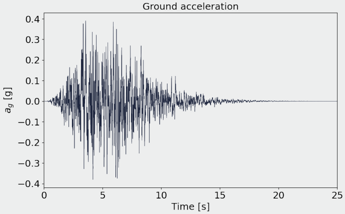
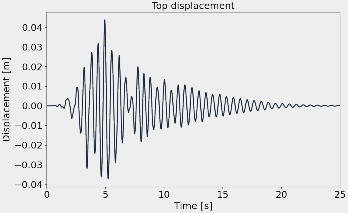
Ground motion

Choice of accelerograms
Here: from a synthetic database



Structural response

Numerical solution
Newmark time integration scheme



Choice of an intensity measure

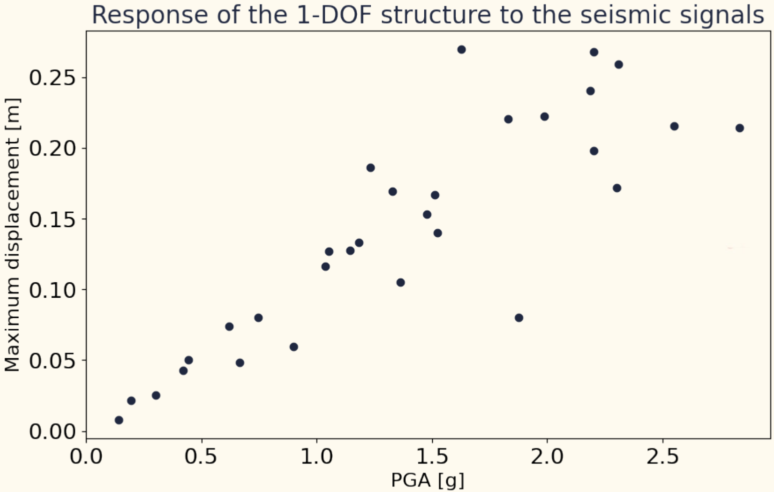
Here: Peak Ground Acceleration

Choice of a damage measure

Here: Maximum top displacement

Results

Example with 30 synthetic accelerograms



Statistical model of the obtained responses

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Lognormal fragility model [Zentner, 2017]

- Damage probability : fragility curve $P_f(\alpha) = P\left(DS \geq ds_i \,/\alpha\right)$

$$P_f(\alpha) = \Phi\left(\frac{\ln(\alpha/A_m)}{\beta}\right)$$

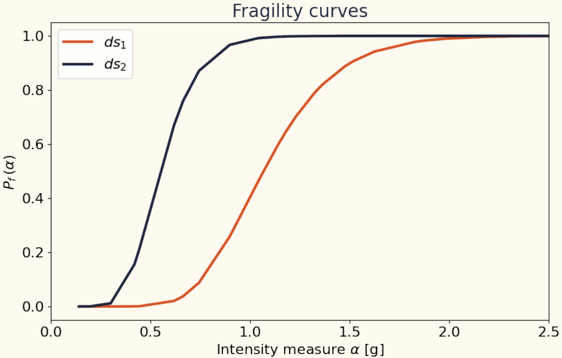
- Identification of parameters A_m, β using the cloud of responses :
  - Either by Maximum Likelihood Evaluation
  - Or by Linear regression (DS as a lognormal variable)

$$\ln(DS) = \ln(b) + c\ln(\alpha) + \ln(\eta)$$

Fragility curves

Application to the example

- DS = maximum displacement, α = PGA
- Identification by linear regression
- Thresholds : $ds_1 = H/200 = 0.1\,m$, $ds_2 = 50\%\,ds_1$.



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Context

[Stocchi et al., 2021] Evaluate the effects of earthquakes on a building typology

- Low to moderate seismic intensity
- Compare predicted damage to in-situ observation

▶ **Fragility curves**

French masonry industrial buildings from the 19th century

Pictures from https://collections.isere.fr/ and [Poursoulis, 2017]

Analysis of the structural variability

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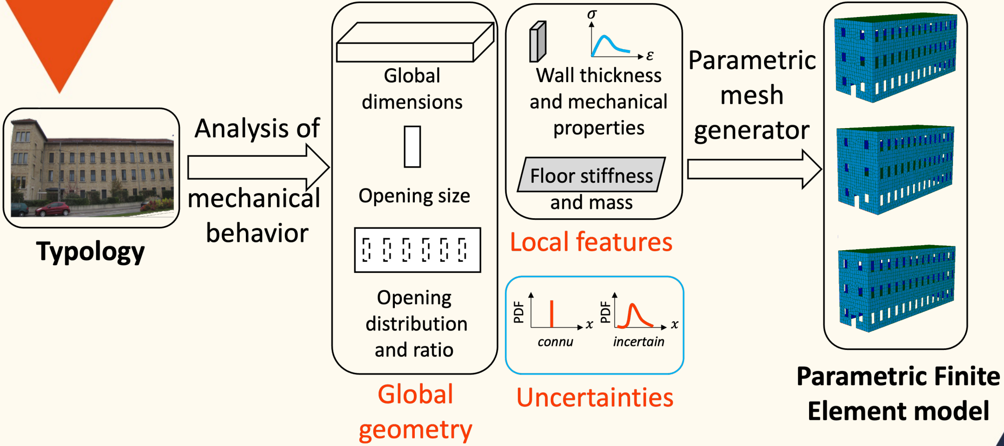


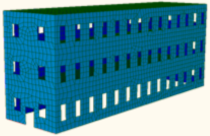
Structural model

- Global modelling strategy based on modal decomposition

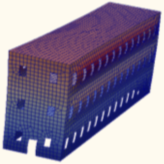
$$\mathbf{U}(t) = \sum_i q_i(t)\mathbf{\Phi_i}$$

- Identification of SDOF oscillators for each mode : $q_i(t)$
  Material non-linearity : unilateral damage model

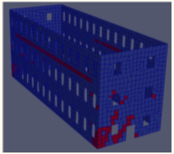
Structural typology



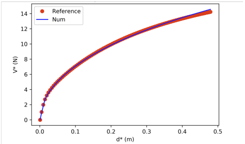
Mesh generation



Mode shapes $\mathbf{\Phi_i}$



Non linear pushover
Applied displacement
$\lambda\mathbf{\Phi_i}$



Identification of the nonlinear SDOF response

- Time history analysis of each SDOF oscillator

$$\ddot{q}_i + 2\,\xi_i\,\omega_i\,\dot{q}_i + f_i(q_i) = \Gamma_i\,a_g(t)$$

Fragility curves

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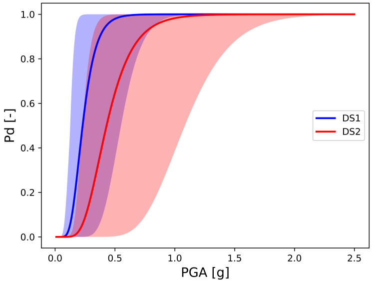
Ground motion

Synthetic database of seismic signals
Intensity measure : PGA

Structural response

Non linear SDOF model
Damage measure : frequency drop-off

Resulting fragility curves - 200 case studies



EigenFrequency Drop Off (EFDO)

- DS1 = $15\,\%$ EFDO $\rightarrow$ Slight damage
- DS2 = $30\,\%$ EFDO $\rightarrow$ Moderate damage

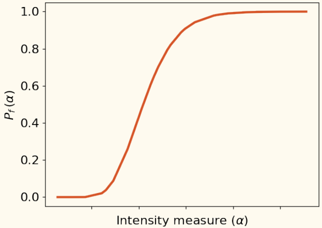
Dispersion $\leftarrow$ Influence of structural uncertainties

Conclusion

Fragility curves

Probability that the damage measure exceeds a defined threshold, given a hazard intensity.

$$P_f(\alpha) = P\left(DS \geq ds_i\,/\alpha\right)$$



Need to define

- DS : Damage State (damage indicator)
- ds_i : Pre-defined damage state threshold
- α : intensity measure

- Useful as a decision-support tool (probabilistic risk assessment)
- Can be used to improve hazard knowledge