# Experimental testing in support of a seismic risk assessment

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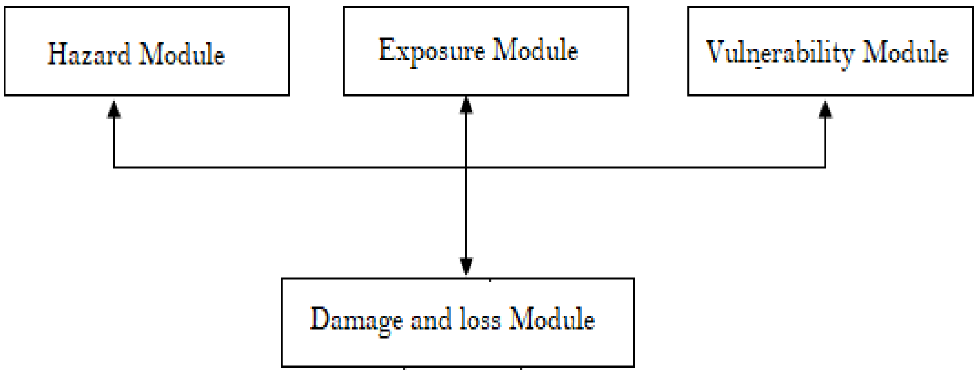
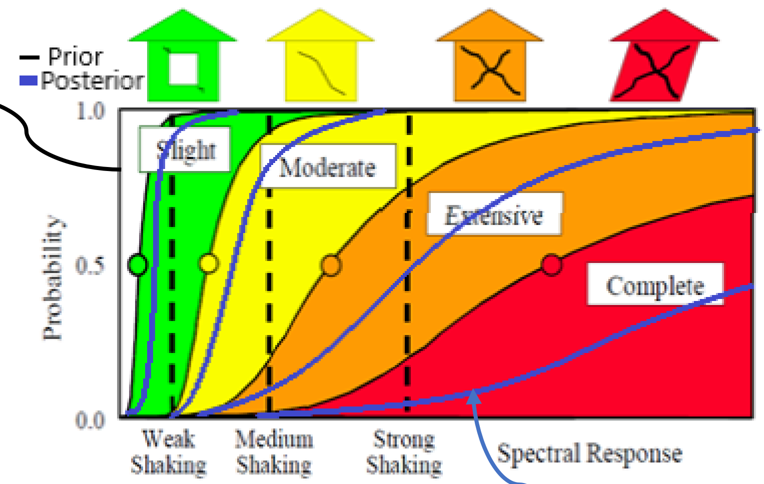
# Outline

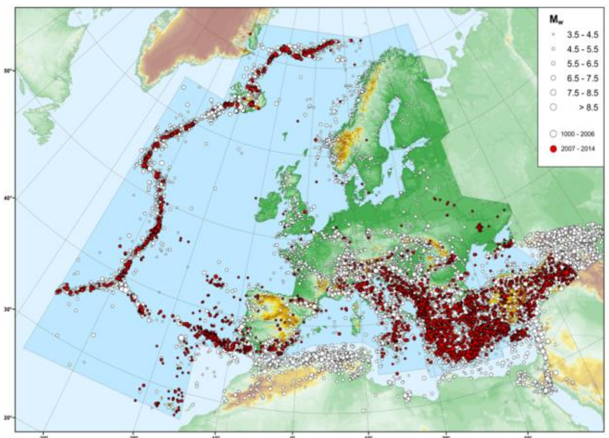
- Introduction
- Methods for Bayesian updating of RC fragility curves
- Maximal utilization of shaking table test output
- Optimal shaking table data for Bayesian updating
- Case study and results
- Conclusion
- Reflections, PhD dissertation and contributions

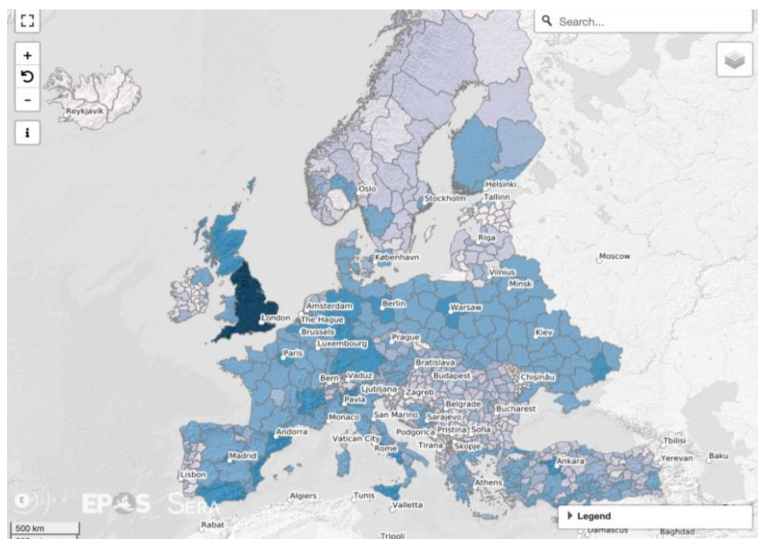
# Introduction: The Big Picture




European Seismic Hazard Model (ESHM13)

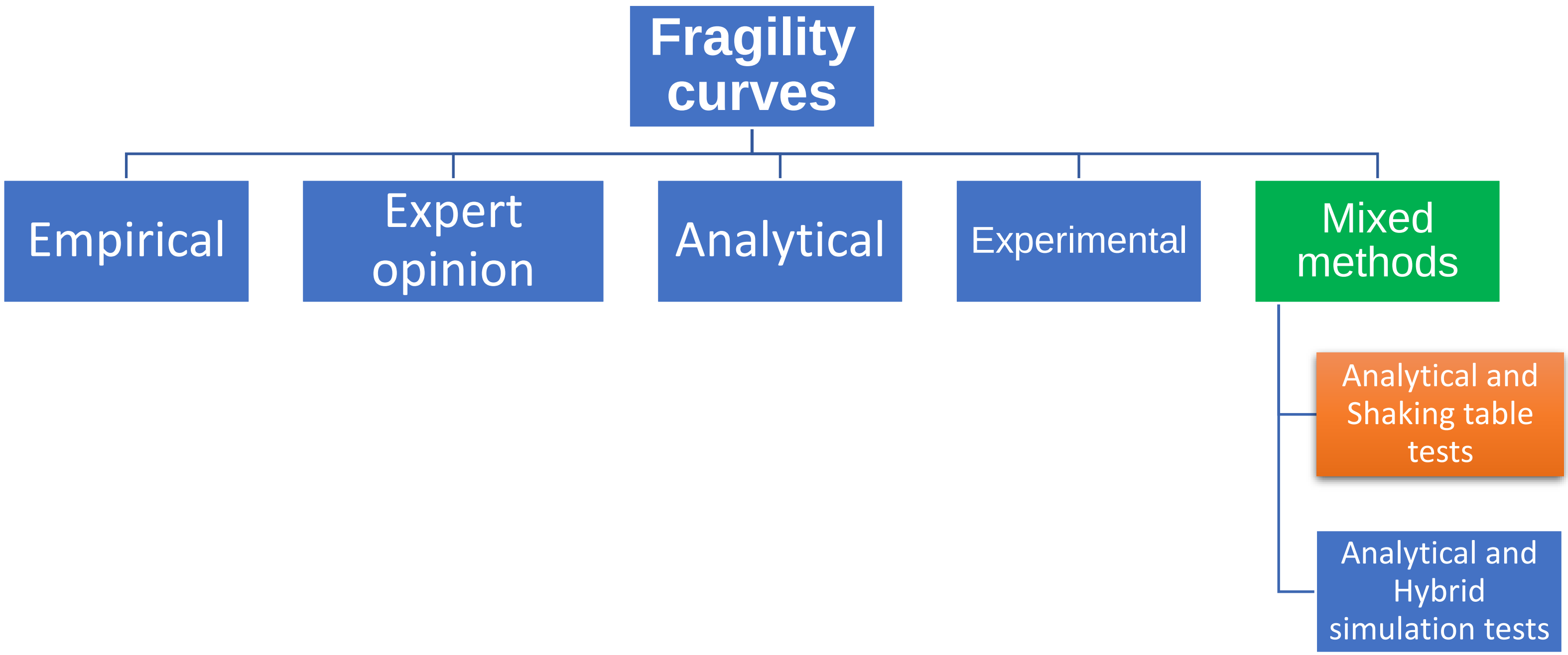



https://maps.eu-risk.eucentre.it/map/european-exposure-level-1/

Prémio Teixeira Duarte, 2014

# Introduction: Fragility curves




Challenges and Opportunities of a mixed method from analytical & shake table tests:

- ✓ Representativeness of a test structure
- ✓ Representativeness of hazard adopted for testing
- ✓ Optimum number of tests for a reliable update
- ✓ Maximal utilization of experimental test outputs
- ✓ Robust and reliable approaches for updating

# Bayesian updating of RC fragility curves: Methods

## Bayesian updating:

$$Pf''_{ds} = P(Pf'_{ds}|Exp) = \frac{P(Exp|Pf'_{ds}) \times Pf'_{ds}}{\sum_{ds} P(Exp|Pf'_{ds}) \times Pf'_{ds}}$$

- Likelihood= $P(Exp|Pf_{ds})$ and Total probability = $\sum_{ds} P(Exp|Pf_{ds})$

## Unscented transformation (UT)/ATC-58:

**Prior:**

$$Pf'_{ds} = \Phi\left(\frac{\ln\left({}^{a}/{}_{A'_m}\right) \; or \; \ln\left({}^{d}/{}_{D'_m}\right)}{\beta'_{ds}}\right)$$

Likelihood (Nonlinear transformation)

**Posterior:**

$$Pf''_{ds} = \Phi\left(\frac{\ln\left({}^{a}/{}_{A''_m}\right) \; or \; \ln\left({}^{d}/{}_{D''_m}\right)}{\beta''_{ds}}\right)$$

$$\beta'_{ds} \sim N(\mu = \beta'_{ds}, \sigma = \alpha_2 \beta'_{ds})$$

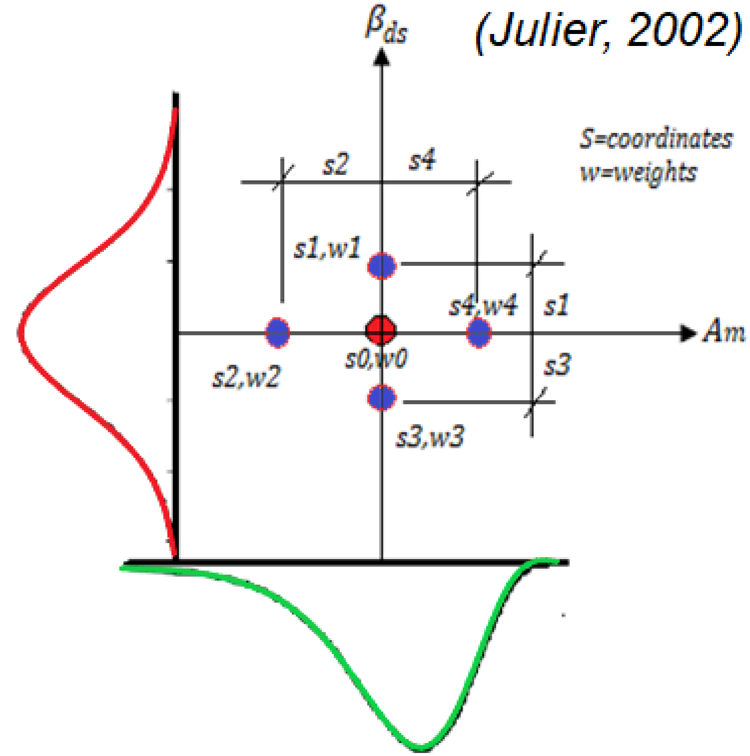
$$A'_m \sim LN(\mu = A'_m, \sigma = \alpha_1 \beta'_{ds})$$

$$A''_m \sim LN(\mu = A''_m, \sigma = \beta''_{ds})$$

# UT method continued…

- Approximates a PDF by few discrete points & assigns coordinates, $s$, and weights, $w'$, for each point *(Porter K. et al, 2007, ATC-58)*
- Weights are updated via the Bayesian framework, using a likelihood $L_j$
- Suppose M samples are tested:
  - P samples don't fail at maximum EDP
  - K samples fail at maximum EDP

*(Julier, 2002)*




$$L_j = \prod_{i=1}^{M} L(s_j, Exp_i) = \prod_{i=1}^{P}\{1-\Phi(d_{j,i})\} \times \prod_{i=1}^{K}(\Phi(d_{j,i}))$$

$$w''_j = \frac{w'_j \times Lj}{\sum_{j=5} w'_j \times Lj} \xrightarrow{\text{update}} \begin{aligned} A''_m &= e^{\sum_{j=1}^{5} w'_j \times ln(A'_m)} \\ \beta''_{ds} &= \sum_{j=1}^{5} w'_j \times \beta'_{ds,j} \end{aligned}$$

# MCMC method

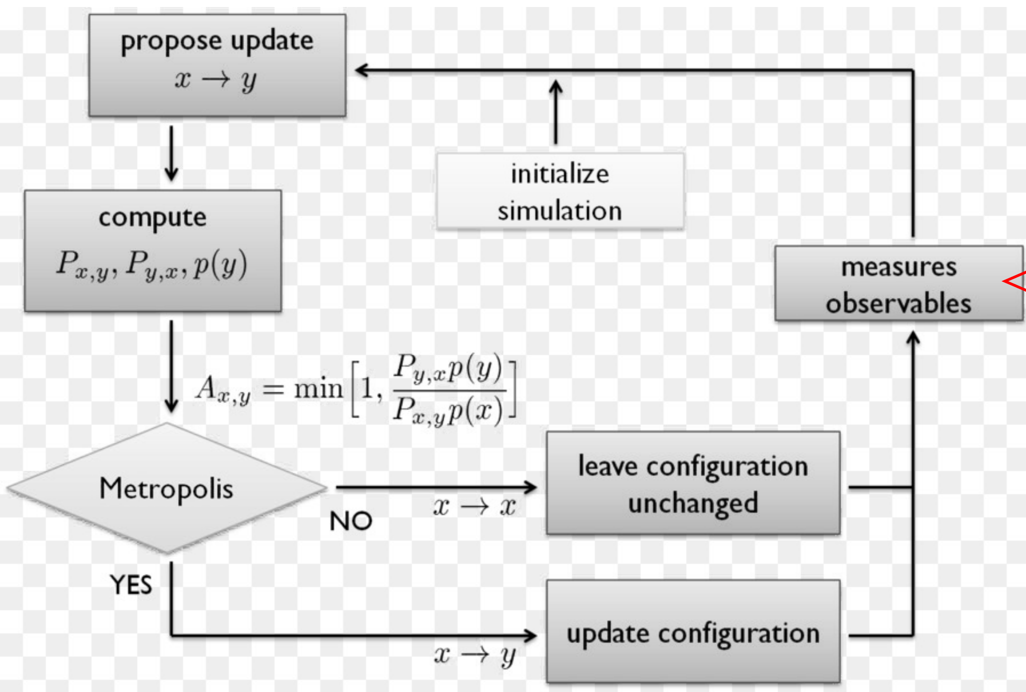
## Markov Chain Monte Carlo (MCMC) method:

$$Pf''_{ds}(\theta_1,\theta_2) \propto L(Data|\theta_1,\theta_2) \times Pf'_{ds}(\theta_1,\theta_2)$$

where $\theta_1 = A_m \; and \, \theta_2 = \beta_{ds}$

$$Pf'_{ds}(\theta_1,\theta_2) = P(\theta_1|\mu_{\theta_1},\sigma^2_{\theta_1}) \times P(\theta_2|c,\lambda)\;;\;\; \theta_1 \sim LN(\mu_{\theta_1},\sigma^2_{\theta_1}) \; and \;\; \theta_2 \sim Gamma(c,\lambda)$$

### Metropolis-Hasting algorithm




Exceedance indicator, $\epsilon_{DS}$

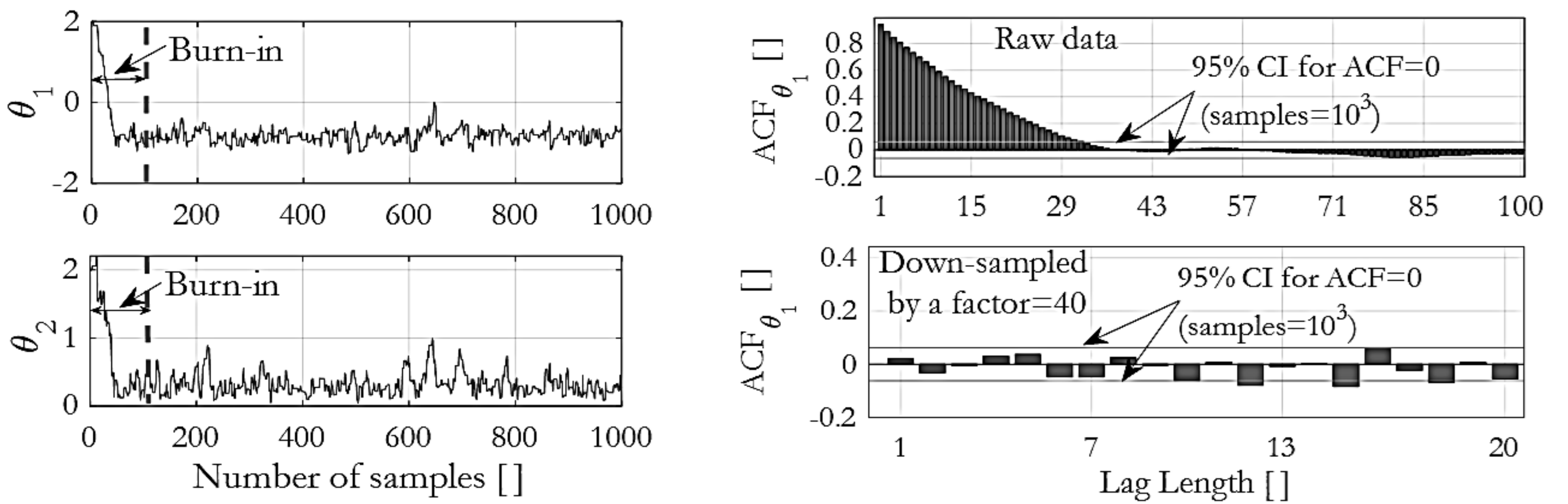
| | | Inter-story drift for HAZUS 2000 Damage states | | |
|---|---|---|---|---|
| | | | 11.5 mm | 18.4 mm |
| Stages | $S_a(T_1)_{eq}$ [g] | $ISD_{max}$ [mm] | Slight | Moderate |
| I | 0.2911 | 7.886 | 0 | 0 |
| 2 | 0.5822 | 15.475 | 1 | 0 |

Precautions:
- Choice of *Proposal PDF*
- Ensuring proper mixing of samples (acceptance ratio, AR, need to be 10-50%)

# MCMC method continued…

## Post-processing samples from MCMC:

- Bias due to Initial condition; *Burning*
- High correlation of samples; *Thinning*

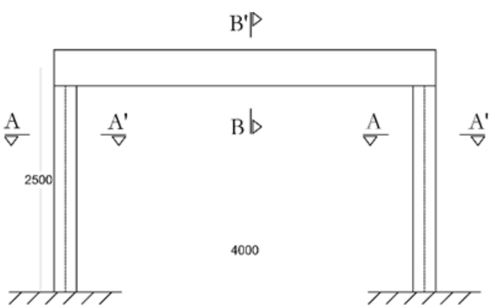


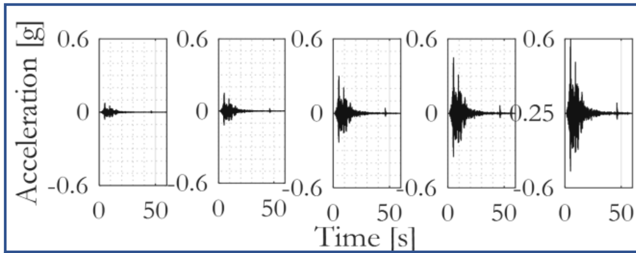

- Fitting a PDF to treated samples can be done through *kernel fitting or* using *known PDFs*

# Maximal utilization of shaking table test output

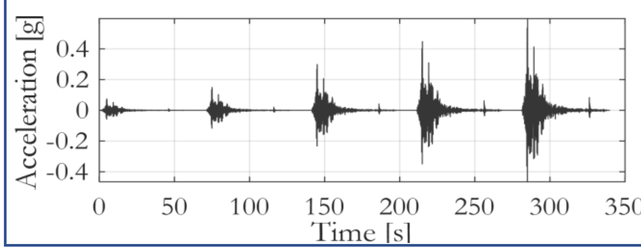
## Index for RC damage:

$$ln(DI) = b\, ln(S_a(T_1)) + ln(a)$$




$$DI_{Non-seq}^{stg_j} = \frac{u_{max}^{stg_j}}{u_{ult}} + \beta \times \frac{E_h^{\ stg_k}}{F_y d_{ult}}$$




$$DI_{seq}^{stg_j} = \frac{u_{max}^{stg_j}}{u_{ult}} + \beta \times \frac{\sum_{k=1}^{j} E_h^{\ stg_k}}{F_y d_{ult}}$$

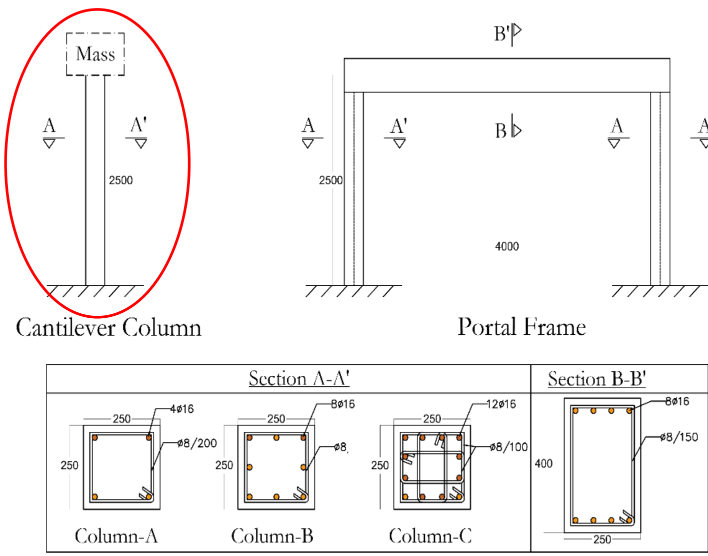
$$S_a(T_1)_{eq} = \left\{\frac{DI_{seq}^{stg_j}}{DI_{Non-seq}^{stg_j}}\right\}^{1/b} \times S_a(T_1) : \ S_a(T_1)_{eq} \geq S_a(T_1)$$

# Maximal utilization continued…

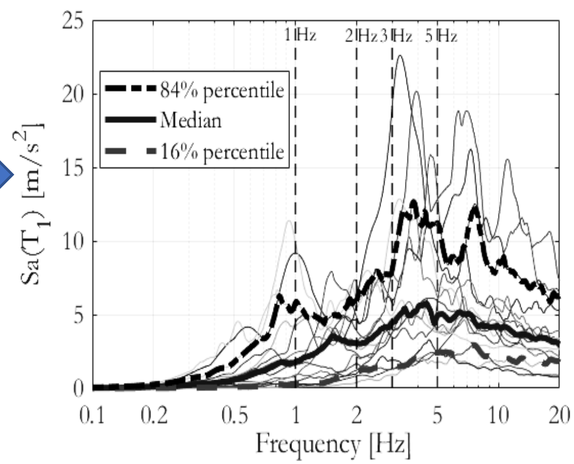
## Parametric Numerical study on $S_a(T_1)_{eq}$ :

Considers:

- Structure type
- Frequency of a structure
- Column cross-section



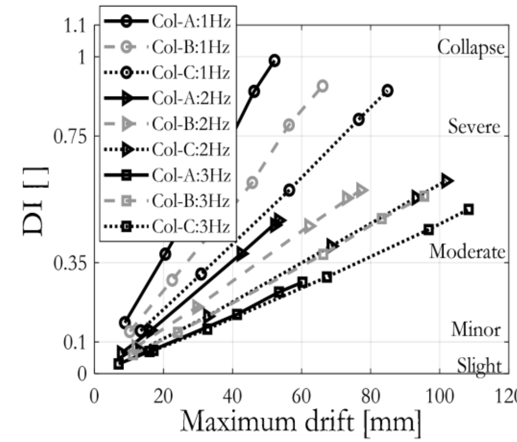

Scaling: $0.5a_y$, $a_y$, $2a_y$, $3a_y$ and $4a_y$



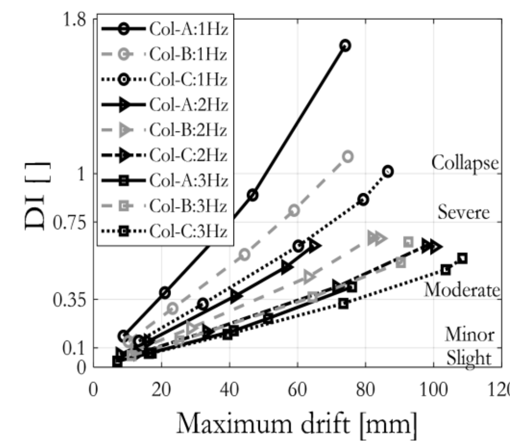

EN 1998–5:2019

Mw=6-6.5

Cantilever: Nonsequential




Cantilever: Sequential



# Maximal utilization continued…

## Parametric Numerical study on $S_a(T_1)_{eq}$ :

*Step-1:* Evaluate $\dfrac{DI_{seq}^{stg_j}}{DI_{Non-seq,\,S_a(T_1)}^{stg_j}}$

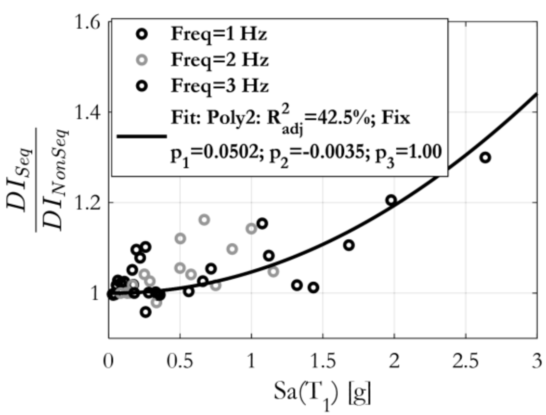
*Step-2 :* Fit for Power coefficient, b, from $ln\left(DI_{Non-seq}^{stg_j}\right) = b\, ln(S_a(T_1)) + ln(a)$

*Step-3:* Redo Non-sequential analysis with $S_a(T_1)_{eq}$

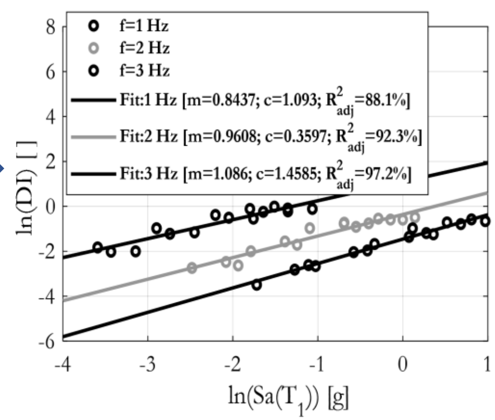
*Step-4:* Compute $\dfrac{DI_{seq}^{stg_j}}{DI_{Non-seq,\,S_a(T_1)_{eq}}^{stg_j}}$ (validation)

Cantilever column results:

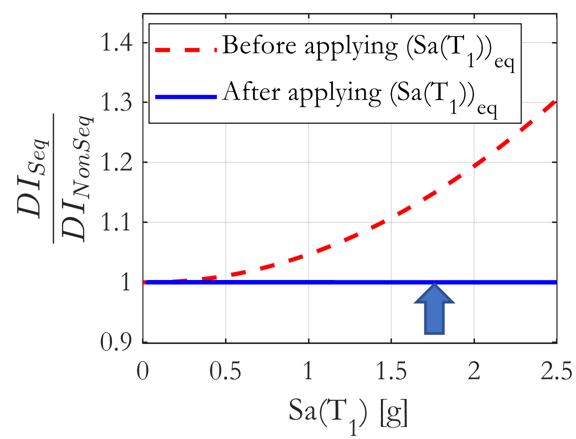
Step-1




Step-2




Step-3/4

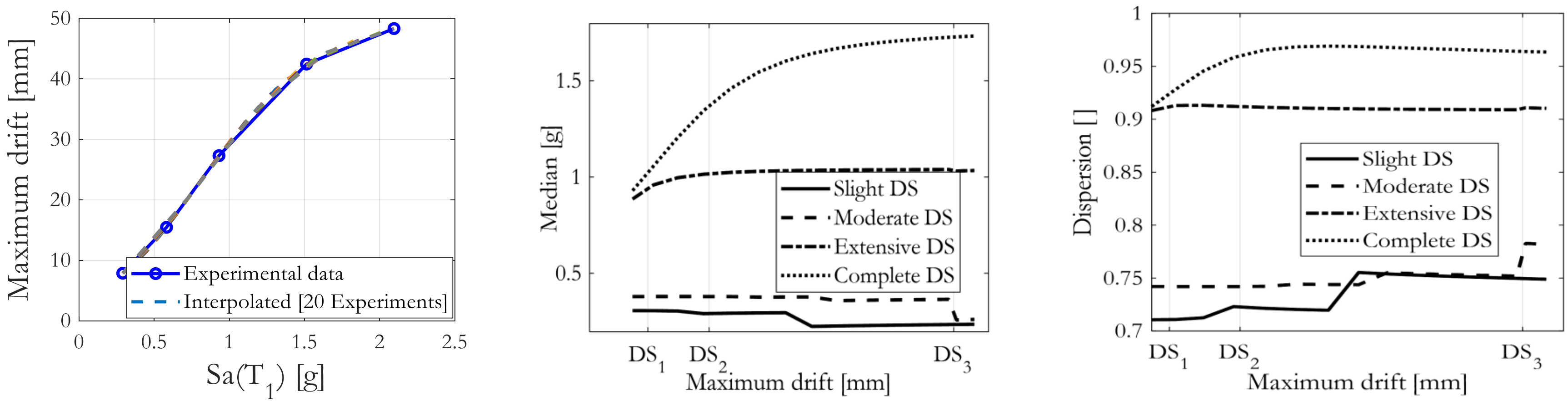


# Optimal shaking table data for Bayesian updating

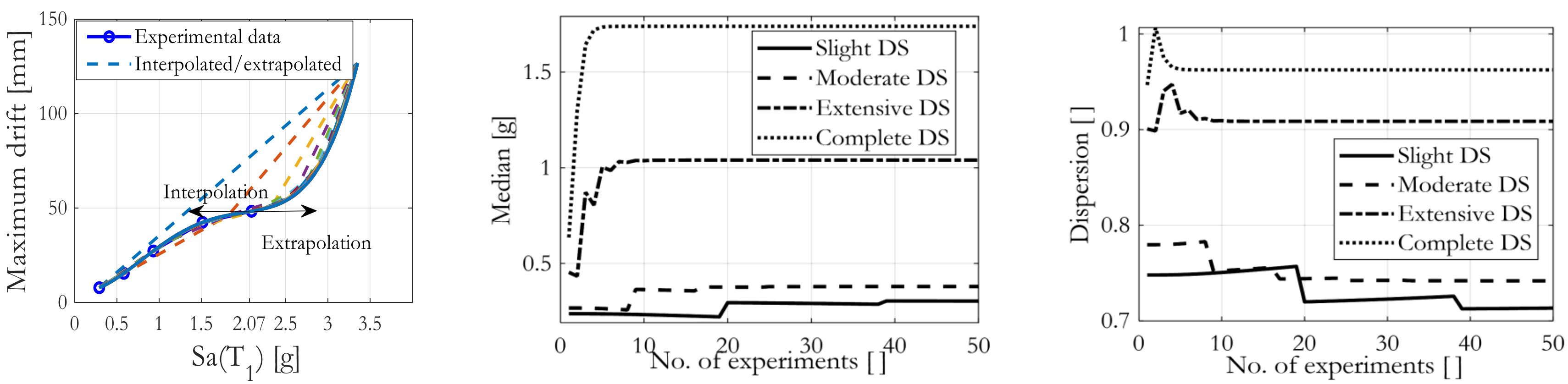
## Parametric study:

- Conducted by interpolating and extrapolating of a case study output, presented subsequently
- Employs ATC-58 procedure since a large number of analyses needs to performed

### Effect of exceeding a particular DS in Bayesian updating

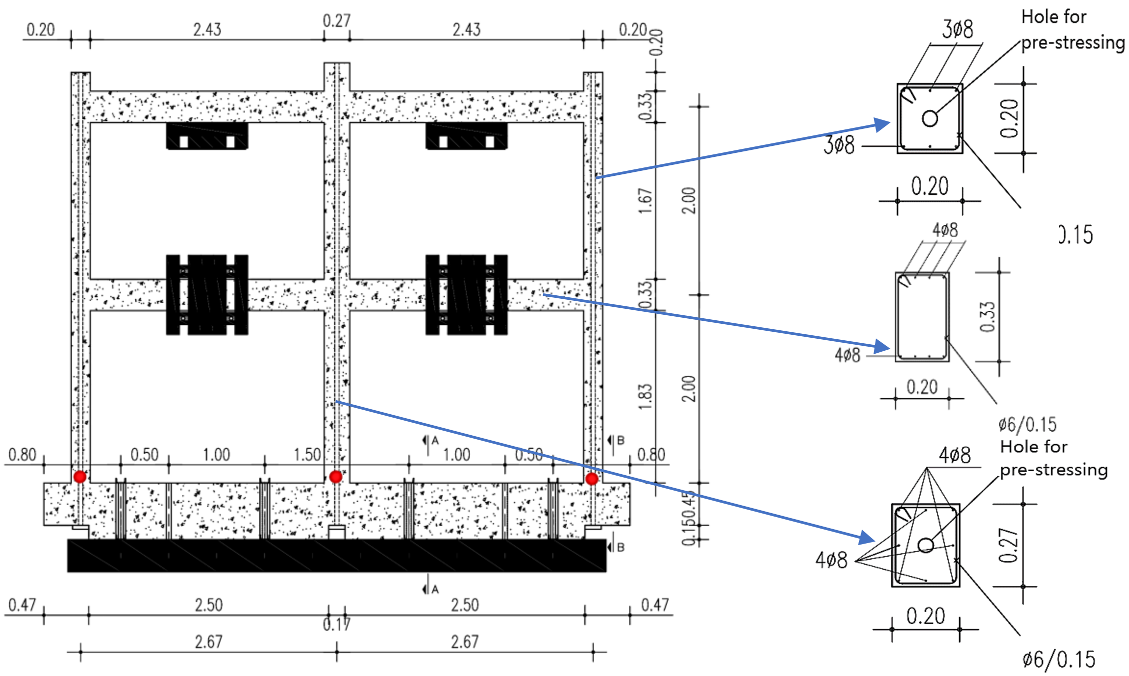


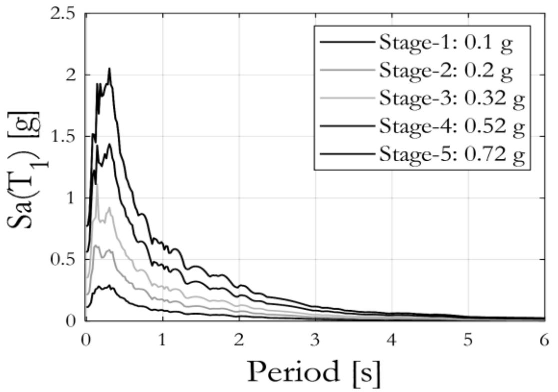

### Optimal number/stages of shaking table tests for Bayesian updating

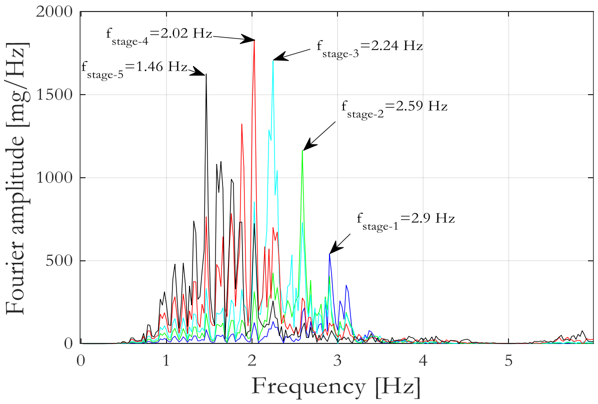


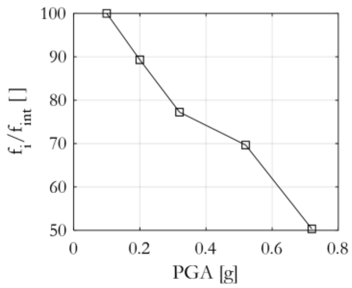
# Case study

**Case study:** 2D RC frame (Prémio Teixeira Duarte, 2014)



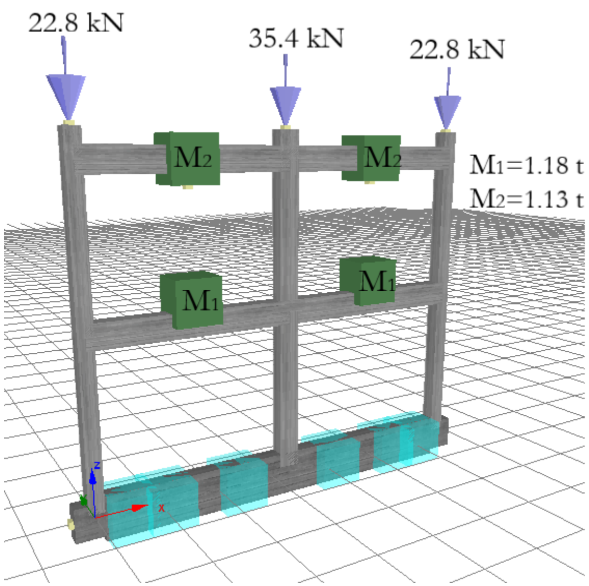



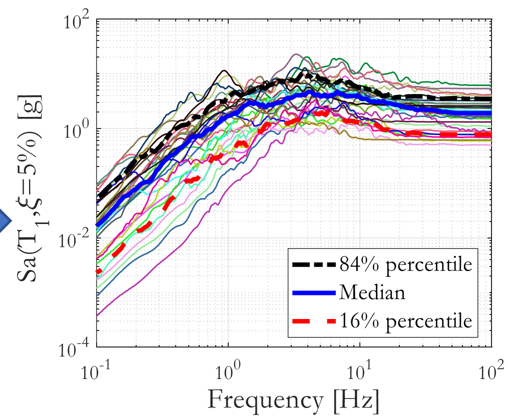



# Case study: Numerical derivation of fragility curves

## Seismostruct model:

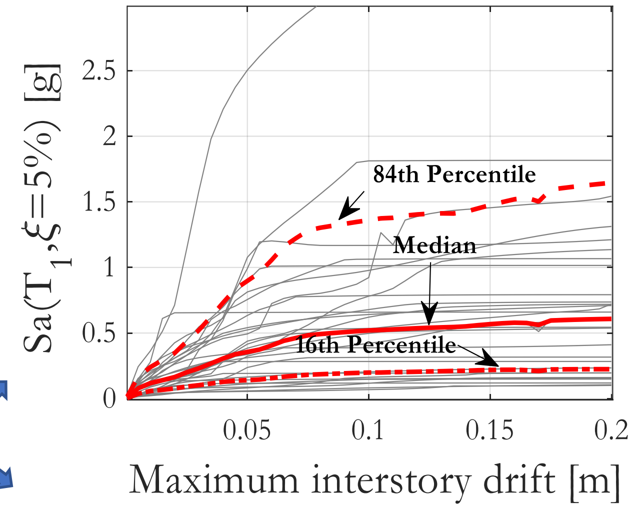


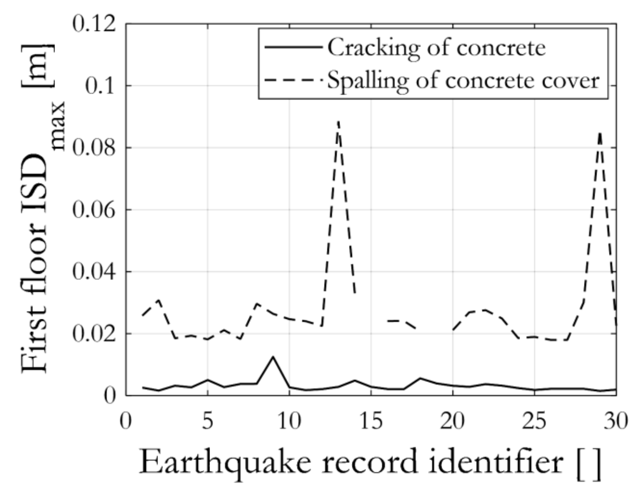

EN 1998–5:2019

Mw=6-6.5

IDA results: 1st floor $ISD_{max}$




IDA results: Strain monitoring at columns

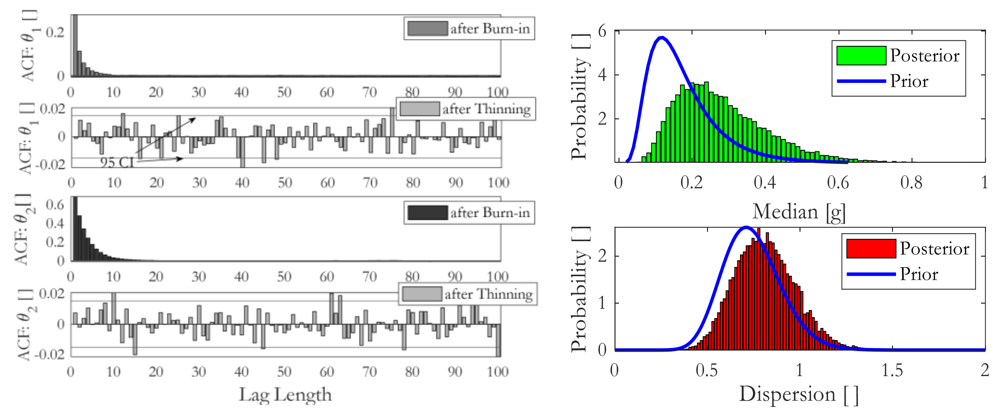


# Application to case study

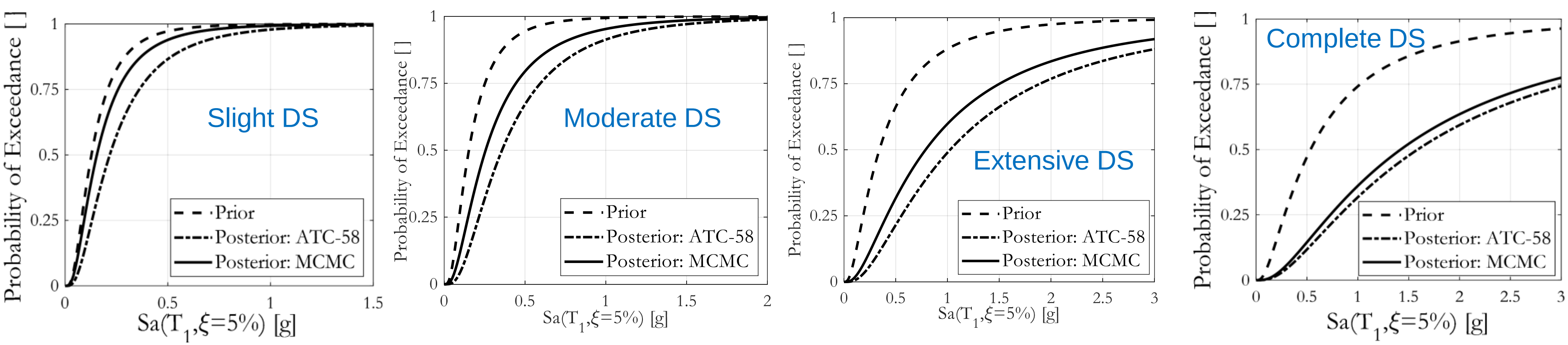
## HAZUS Damage State (HAZUS, 2000):

Pre & Post processing: Moderate DS

| | | | | Inter-story drift for HAZUS 2000 Damage states | | | |
|---|---|---|---|---|---|---|---|
| | | | | 11.5 mm | 18.4 mm | 46 mm | 118 mm |
| Stages | $S_a(T_1)$ [g] | $S_a(T_1)_{eq}$ [g] | $ISD_{max}$ [mm] | Slight | Moderate | Extensive | Complete* |
| 1 | 0.2911 | 0.2911 | 7.886 | 0 | 0 | 0 | 0 |
| 2 | 0.5822 | 0.5822 | 15.475 | 1 | 0 | 0 | 0 |
| 3 | 0.9316 | 0.9316 | 27.321 | 1 | 1 | 0 | 0 |
| 4 | 1.5138 | 1.5138 | 42.453 | 1 | 1 | 0 | 0 |
| 5 | 2.0960 | 2.0960 | 48.323 | 1 | 1 | 1 | 0 |




Acceptance ratio (AR) = 30-35%

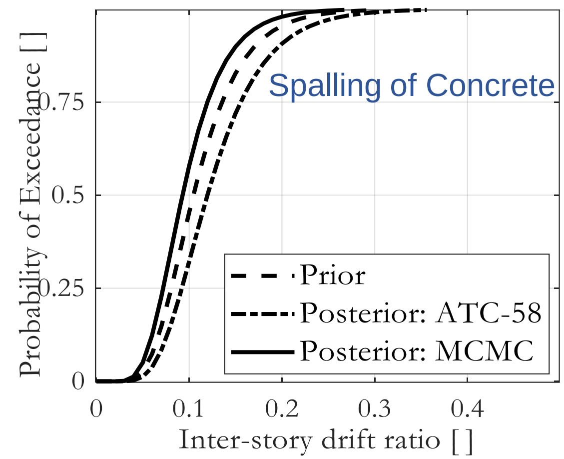


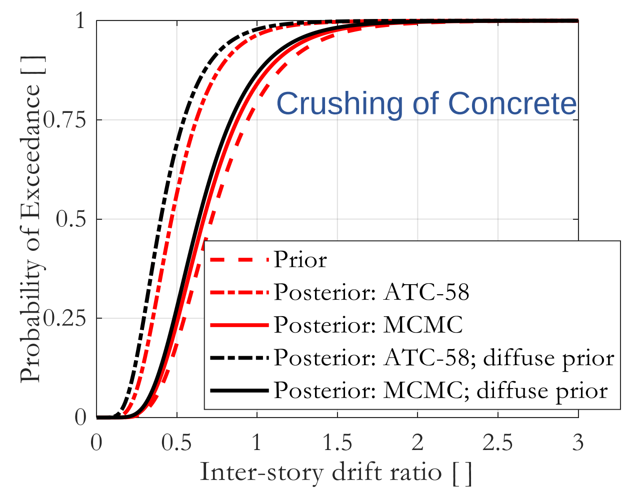

Summary: In all cases, the ATC-58 approach results in a lower fragility compared to the MCMC method

# Application to case study continued…

## Strain-based (or physical) Damage States:

| | | Visual inspection | | | |
|---|---|---|---|---|---|
| Test stages | $ISD_{max}$ [mm] | Cracking | Spalling | Yielding | Crushing |
| 1 | 7.886 | 0 | 0 | 0 | 0 |
| 2 | 15.475 | 1 | 0 | 0 | 0 |
| 3 | 27.321 | 1 | 0 | 0 | 0 |
| 4 | 42.453 | 1 | 1 | 0 | 0 |
| 5 | 48.323 | 1 | 1 | 1 | 1 |



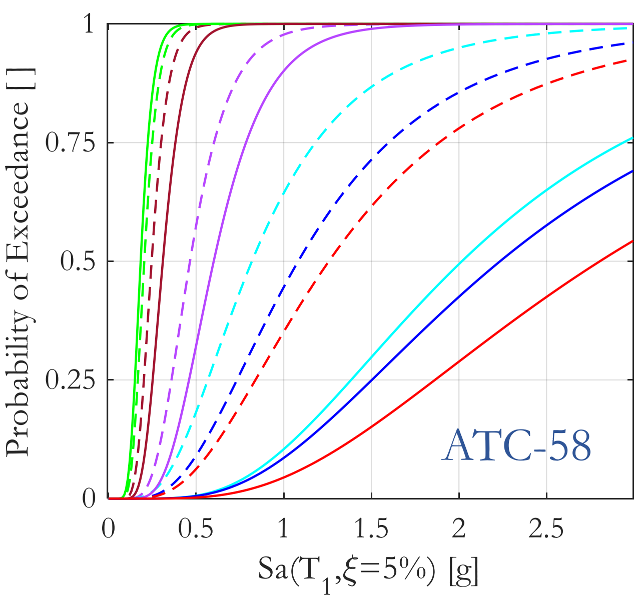



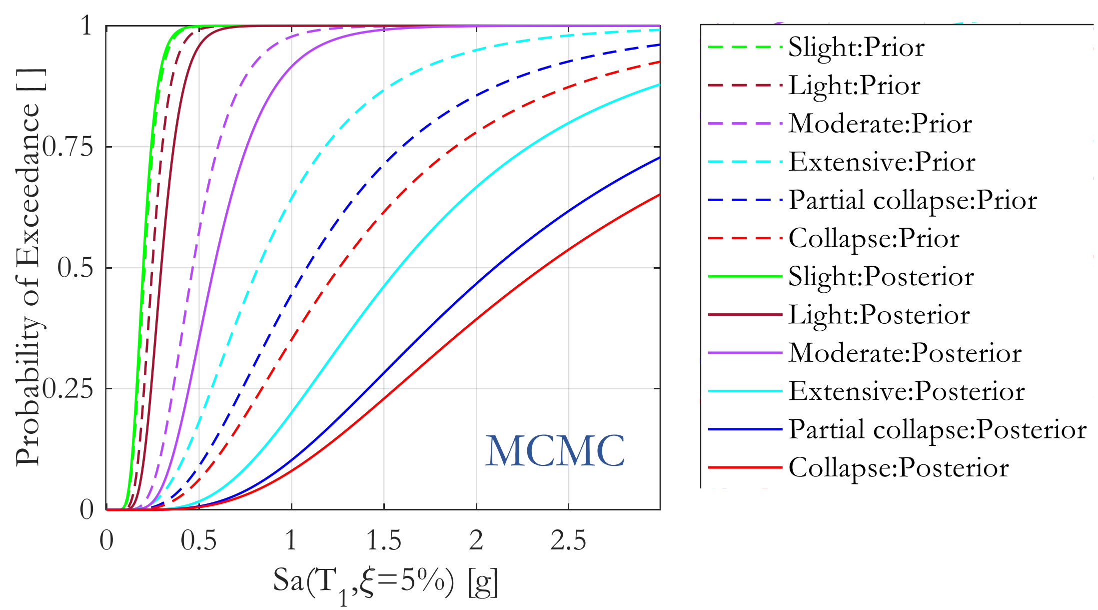

Note: MCMC is more robust to diffuse priors, important when an unreliable prior is present

# Application to case study continued…

## Homogenized reinforced concrete (HRC) Damage States (Elnashai and Rossetto, 2003) :

| | | | | Exceedance, ε, for HRC Damage states (DS) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 7.36 mm | 9.89 mm | 23.46 mm | 55.43 mm | 98.21 mm | 130.64 mm |
| **S**tages | $S_a(T_1)$ [g] | $S_a(T_1)_{eq}$ [g] | $ISD_{max}$ [mm] | Slight | Light | Moderate | Extensive | Partial collapse | Collapse |
| 1 | 0.2911 | 0.2911 | 7.886 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.5822 | 0.5822 | 15.475 | 1 | 1 | 0 | 0 | 0 | 0 |
| 3 | 0.9316 | 0.9316 | 27.321 | 1 | 1 | 1 | 0 | 0 | 0 |
| 4 | 1.5138 | 1.5138 | 42.453 | 1 | 1 | 1 | 0 | 0 | 0 |
| 5 | 2.0960 | 2.0960 | 48.323 | 1 | 1 | 1 | 0 | 0 | 0 |



# Conclusion

- This work shows that the output of shaking table tests can be used for improving the fidelity of seismic risk assessment if used carefully
- The scheme proposed for obtaining the modified intensity measure for sequential shake table tests resulted in negligible modification factors for damage indices below 0.75. Besides, larger dispersion of this modification factor was observed in more complex structures
- Bayesian updating of fragilities is more reliable when the damage states are exceeded during the experimental tests
- MCMC based Bayesian updating was found more reliable and robust compared to the ATC-58 procedure. However, it is noteworthy that it needs proper mixing of samples
- MCMC based Bayesian updating may result in erroneous values if prior PDFs are poorly chosen and a small number of experimental tests is used

# Reflections, PhD dissertation & contributions

*Chapter -1*

- Introduction

**Literature Review**

*Chapter-2*

- Literature Review on Hybrid Simulation

*Chapter-3*

- Simulated Hybrid Testing of Structures-Applications

*Chapter-4*

- Development and Validation of a Software Framework for Hybrid Simulation

*Chapter-5*

- Soil-Structure Interaction Test in Hybrid Simulation

*Chapter-6*

- Bayesian Updating of RC Fragilities using Shaking Table tests

*Chapter-7*

- Conclusions and Future works

# Contributions

*Tekeste, G.G., Correia, A.A. [2016] "LNEC hybrid simulation tools and future developments", Workshop Hybrid 2020: State-of-the-art and future directions for hybrid modelling and simulation, ETH, Zurich, Switzerland*

*Tekeste, G.G., Correia, A.A., Costa, A. G., [2017] "Virtual hybrid simulation tests accounting for experimental errors", OpenSees Days Europe: First European conference on OpenSees, Porto, Portugal*

*Tekeste, G.G., Correia, A.A., Costa, A. G., [2017] "Stability analysis of a real-time shake table hybrid simulation for linear and non-linear SDOF systems", 7$^{th}$ International Conference on Advances in Experimental Structural Engineering, EUCENTRE Foundation, Pavia, Italy*

*Tekeste, G.G., Correia, A.A. [2017] "Real-time hybrid simulation in shake table tests – development and application to soil-structure interaction systems", H2020 Project SERA, JRA5 Meeting, LNEC, Lisbon, Portugal*

*Tekeste, G.G., Correia, A.A. [2018] "Framework for hybrid tests developed at LNEC and its application to soil-structure interaction", H2020 Project SERA, JRA5 Meeting, Istanbul, Turkey*

*Tekeste, G.G., Correia, A.A., Costa, A. G., [2019] "Reliability and global sensitivity analysis in hybrid simulations using surrogate probabilistic modelling", 11º Congresso Nacional de Sismologia e Engenharia Sísmica, IST, Portugal*

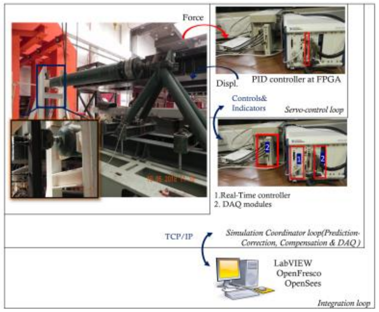
# Contributions continued…

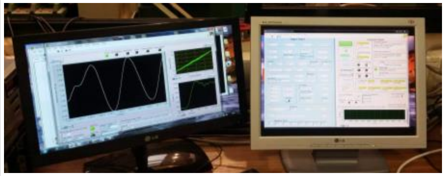
*Correia, A.A., Benavent, A., Bousias, S., Tekeste, G.G., Stojadinovic, B., Abbiati, G. [2019] " Experimental tests by HDS and shaking tables", H2020 Project SERA, JRA5 M27.2 Deliverable*

*Correia, A.A., Benavent, A., Bousias, S., Tekeste, G.G., Abbiati, G., Stojadinovic, B. [2020] "Use of improved hybrid dynamic simulation for novel isolators/dissipators, for thermomechanical applications, and for soil-structure interaction studies", Deliverable 27.3 (WP27-JRA5), SERA – EU H2020 Project.*

## Software and algorithms

**MATLAB/Simulink based**
- Routh stability routines
- Bouc-Wen nonlinear model for substructuring tests
- M-DRM algorithms for global sensitivity & reliability analysis
- MCMC algorithm for Bayesian updating



**LabVIEW based**
- LNEC-HS software
  - OpenFresco based middleware
  - Middleware free


Thank you for your support and attention!

gtekeste@lnec.pt