Experimental testing in support of a seismic risk assessment

Gidewon Goitom Tekeste

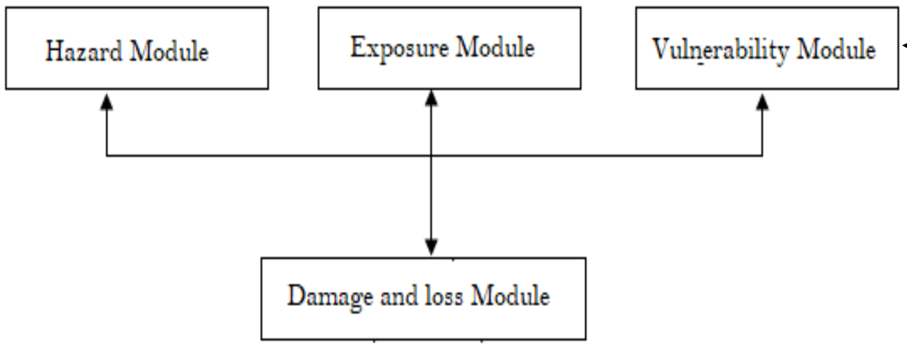
Laboratório Nacional de Engenharia Civil &

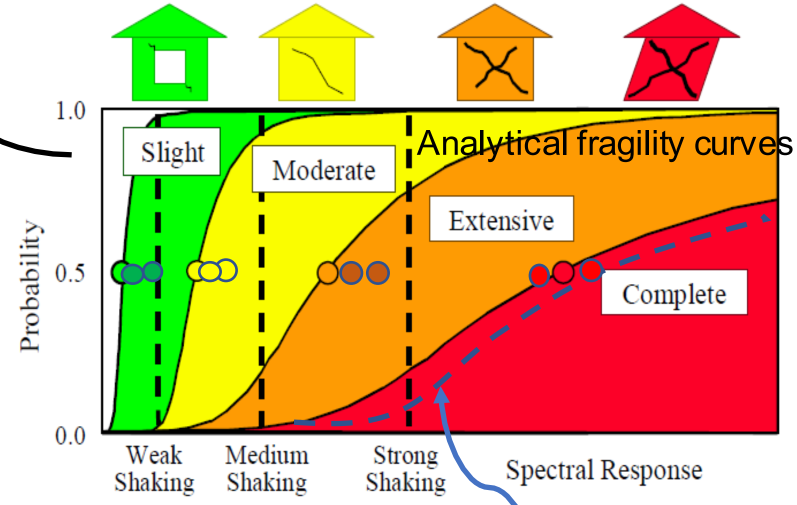
University of Aveiro

Outline

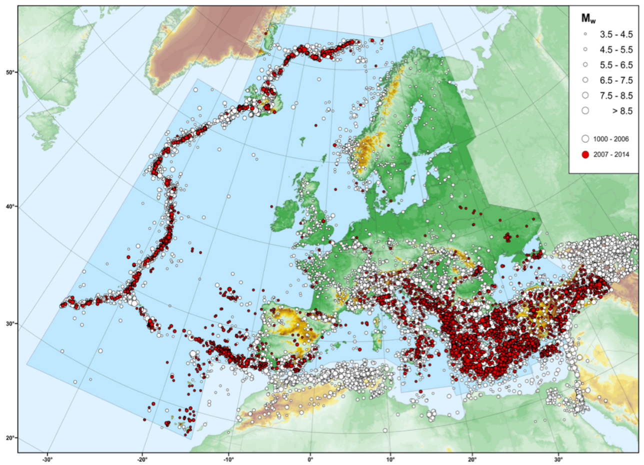
- Introduction
- Tools for seismic risk assessment
- Updating fragility curves: methodology
- Effective intensity measure in sequential shake table testing
- Methodology in updating fragility curves: Bayesian updating
- Case study and results
- Progress chart and hybrid simulation
- Conclusion

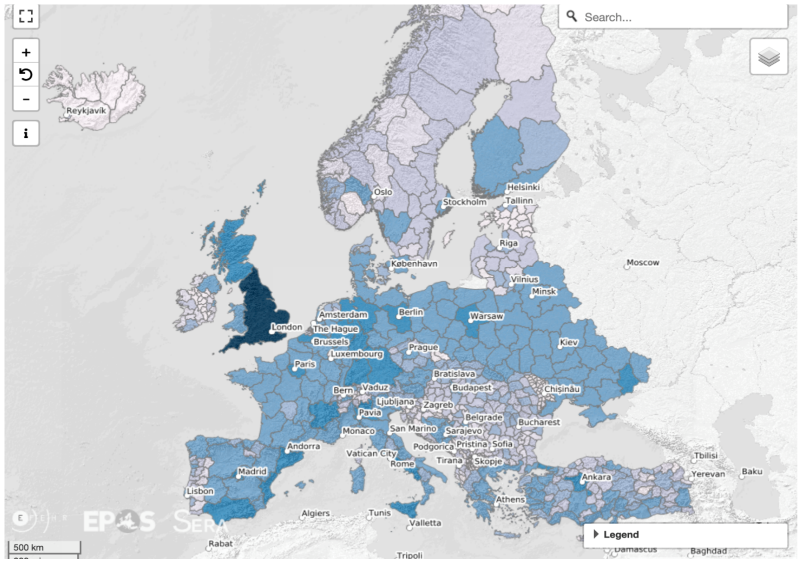
Introduction





European Seismic Hazard Model (ESHM13)





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

Mendes et al., 2014

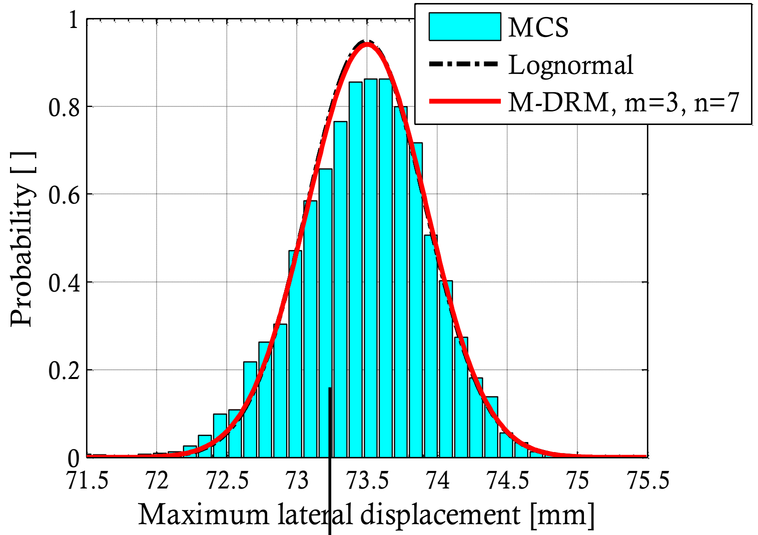
Hybrid testing (HS) in seismic risk framework

- ✓ Capacity in model structural uncertainties

Steps followed:

1. Model structural uncertainties (in numerical sub-structure)
2. Use M-DRM meta model to sufficiently reduce the number of hybrid tests
3. Apply Entropy principle in order to optimize an empirical PDF function via fractional moments

- ✓ Useful in modeling uncertainty in cases where there is no appropriate numerical model for component



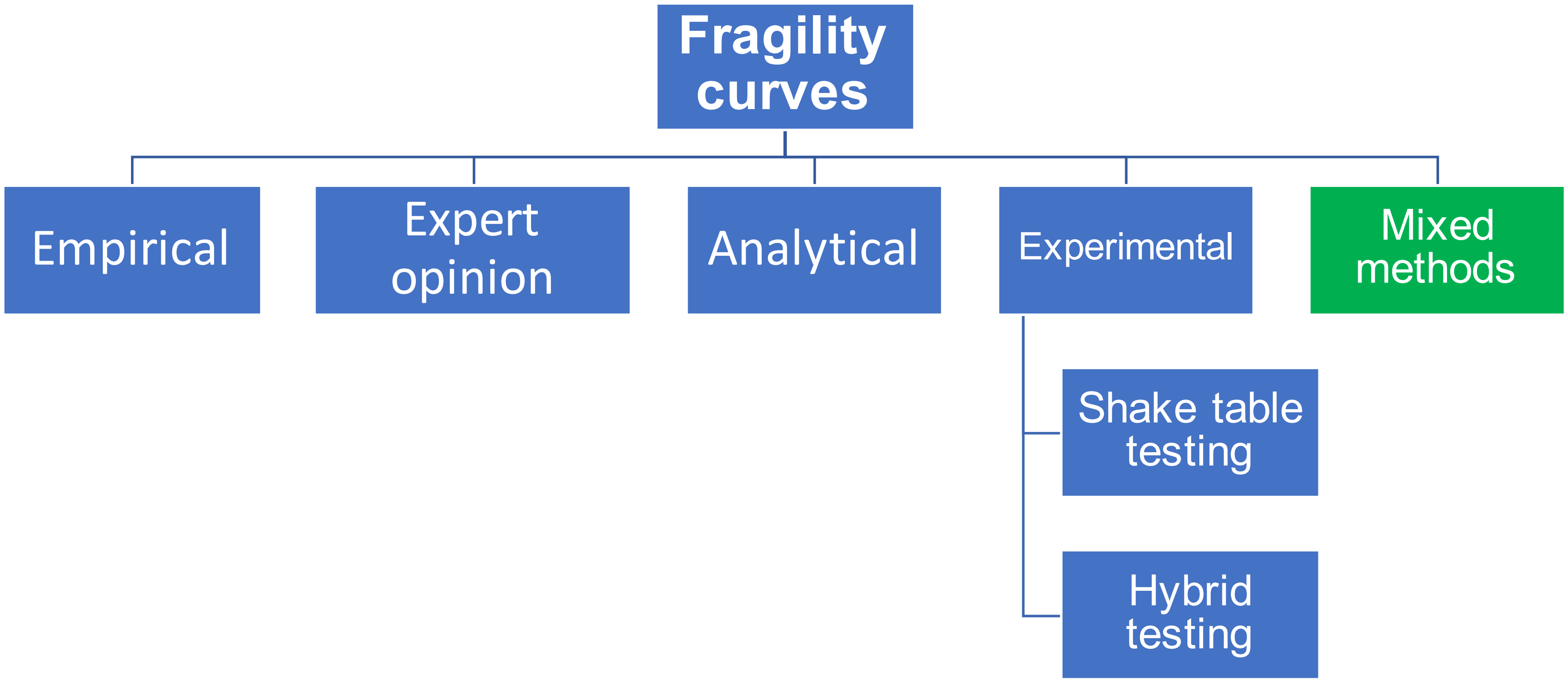
$$Pf_{ds} = \Phi\left(\frac{\ln\left(a/A_m\right)}{\beta_{ds}}\right)$$

$$\beta_{ds} = \sqrt{(\beta_C)^2 + (\beta_D)^2 + \left(\beta_{T,ds}\right)^2}$$

Detailed information can be found on:

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

Tools for seismic risk assessment: Fragility curves



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

- ✓ How representative is the structure tested and the ground motion used?
- ✓ What are the minimum no. of tests in order to update vulnerability?

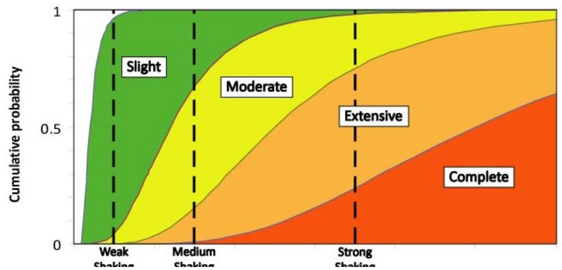
Most importantly, how to maximize the information from experimental tests!

How to update

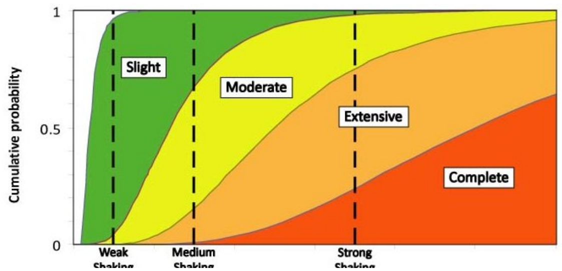
Update can be based on:

- Engineering Demand Parameter (EDP) such as drift or observed data
- Input intensity measure (IM)

  such as Sa(T1)



Spectral displacement



Intensity measure [Sa(T1)]

- Representative input motion (hazard)
- Difficulty in defining increments of input motion in sequential testing (Experimental tests need to be designed carefully)
- Exceedance and updating process can be solely decided based on EDP observed or in combination with IM
- Past experimental tests may also be readily used for updating if they are representative

Updating fragility curves: Methodology

Bayesian update:

$$P(Pf_{ds}|Exp) = \frac{P(Exp|Pf_{ds}) \times Pf_{ds}}{\sum_{ds} P(Exp|Pf_{ds}) \times Pf_{ds}}$$

- $L = P(Exp|Pf_{ds})$

Unscented transformation (UT)

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:

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

$$A_m \sim LN(\mu = A_m, \sigma = \alpha_1 \beta_{ds})$$

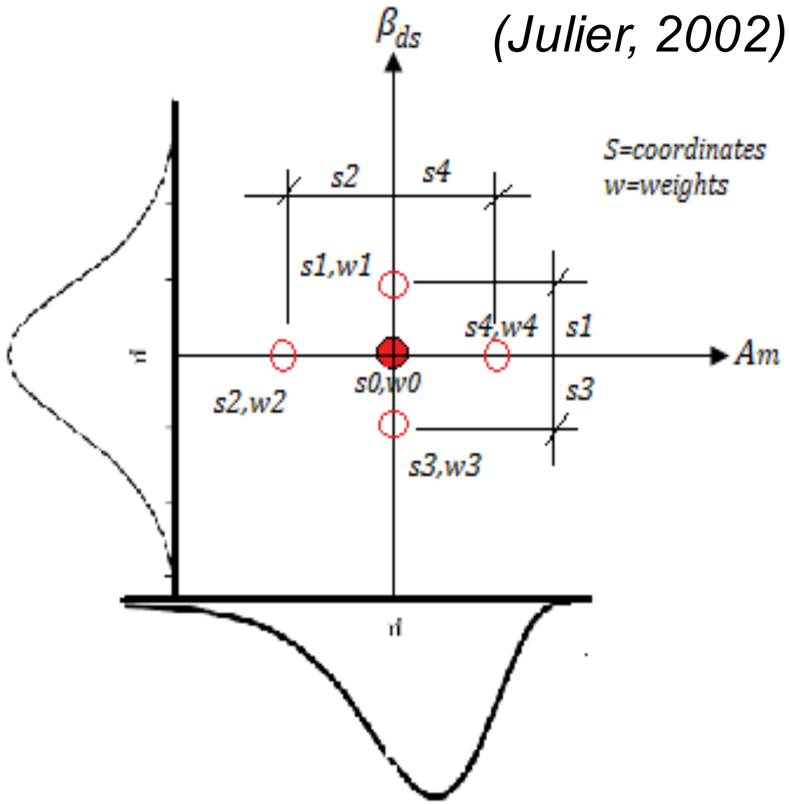
$$\beta_{ds} \sim N(\mu = \beta_{ds}, \sigma = \alpha_2 \beta_{ds})$$

Updating fragility curves: Methodology

Unscented Transformation (UT):

- Approximates a distribution by few discrete points & assigns coordinates and weights for each *(Porter K. et al, 2007, ATC-58)*
- Weights are updated by Bayesian method via a likelihood, L_j
- Suppose M samples are tested:
  - P samples don't fail at max. EDP
  - K samples fail at an observed EDP &
  - R samples fail but max. EDP is only known

(Julier, 2002)



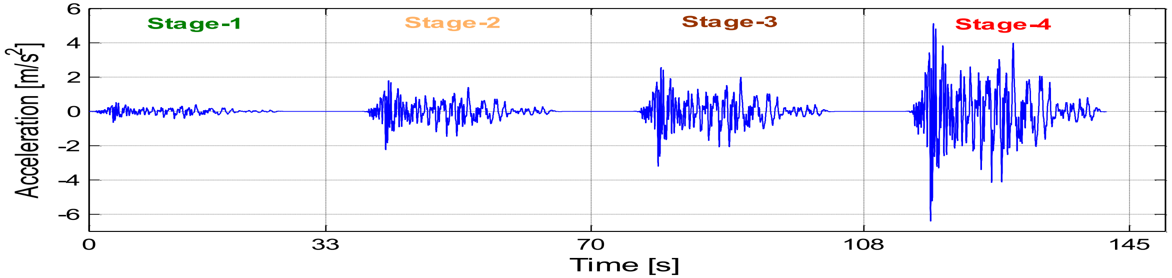
$$L_j = \prod_{i=1}^{M} L(s_j, Exp_i) = \prod_{i=1}^{P}\{1-\Phi(d_{j,i})\} \times \prod_{i=1}^{R} \Phi(d_{j,i}) \times \prod_{i=1}^{K}(\phi(d_{j,i}))$$

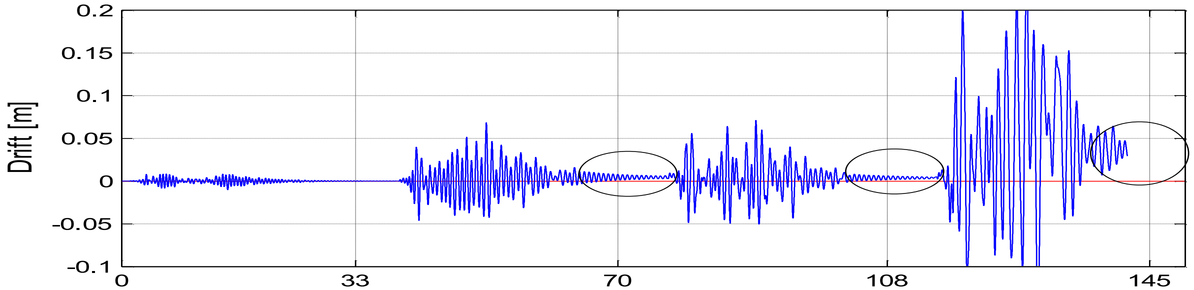
$$w'_j = \frac{w_j \times Lj}{\sum_{j=5} w_j \times Lj} \xrightarrow{\text{update}} \begin{aligned} A'_m &= e^{\sum_{j=1}^{5} w'_j \times ln(A_m)} \\ \beta'_{ds} &= \sum_{j=1}^{5} w'_j \times \beta_{ds,j} \end{aligned}$$

Effective intensity measure in sequential shake table testing

Shake table tests:

- Shake table test information can be maximized by considering stages of a single earthquake record as independent tests
- Sequential testing involve damage accumulation
- Equivalent IM for stages with cumulative damage is necessary. It can based on:
  - Maximum drift
  - Damage Index
  - Energy absorbed etc.



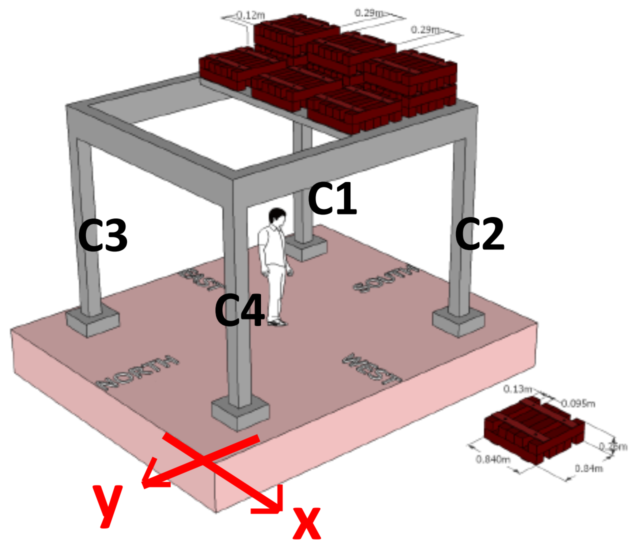


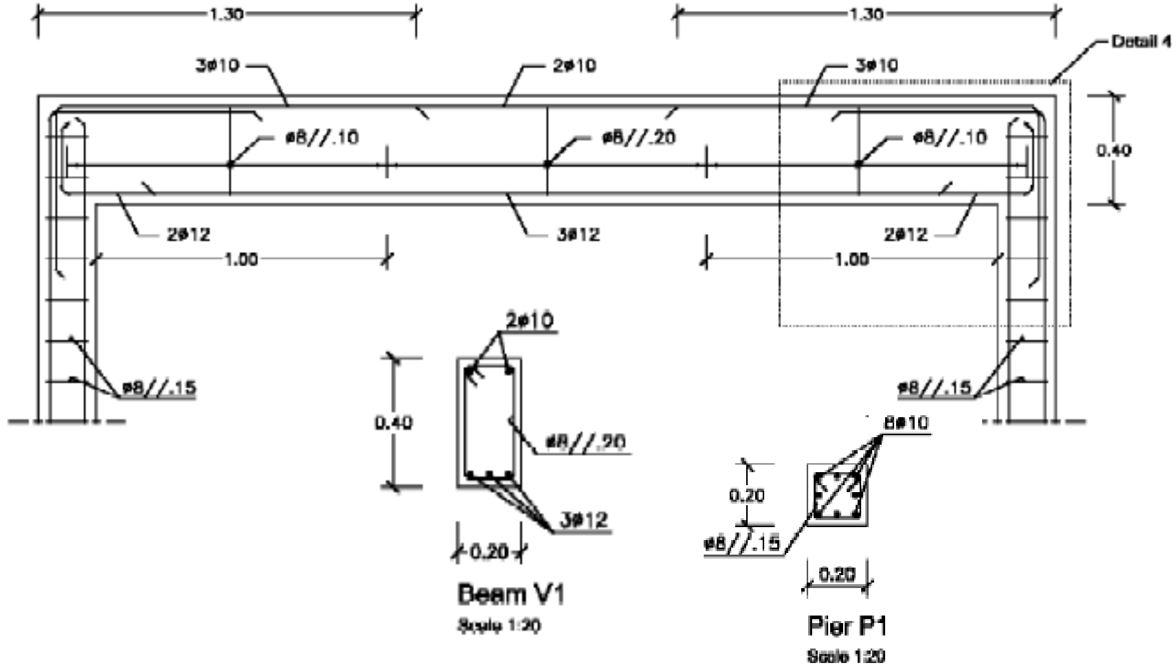
Tentative modification factors considering Sa(T1) as an IM:

Based on data from sequential testing	Based on parametric tests apriori
$Sa(T1)_{eq}{}^{stg_i} = Sa(T1)^{stg_i} \times \dfrac{IM_{est}^{stg_i} / Sa(T1)^{stg_i}}{IM_{est}^{stg_{i-1}} / Sa(T1)^{stg_{i-1}}}$	$Sa(T1)_{eq}{}^{stg_i} = Sa(T1)^{stg_i} \times \dfrac{EDP^{Cum^{stg_i}}}{EDP^{Indp^{stg_i}}}$
$\ln(EDP^{stg_i}) = b^{stg_i} \times \ln(IM_{est}^{stg_i}) + \ln(a^{stg_i})$	**EDP=ISDR or DI**; $DI^{Cum^{stg_i}} = \dfrac{d_{max}^{stg_i}}{d_{ult}} + \beta \times \dfrac{\sum_{k=1}^{i} E_h{}^{stg_k}}{F_y d_{ult}}$

Case study: Numerical analysis

Case study: 3D RC frame (Blind prediction test at LNEC, 2012)





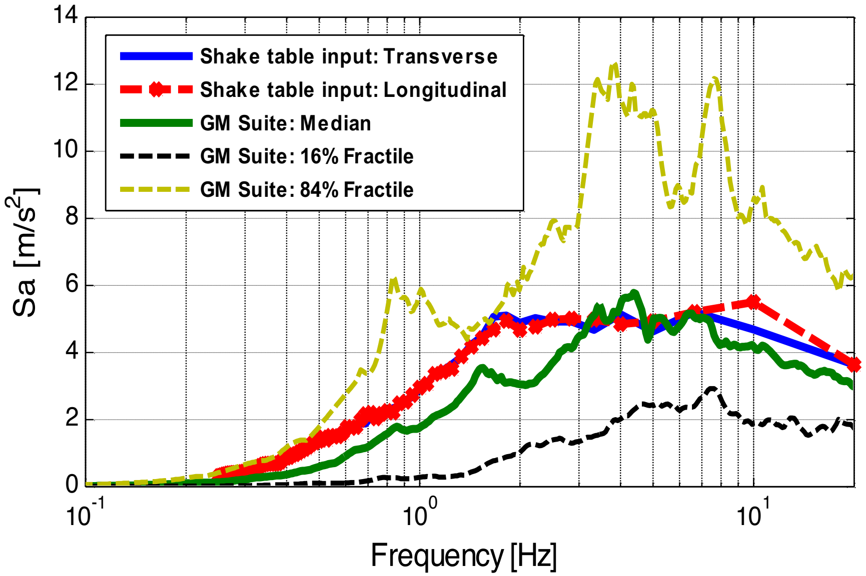
Objectives: Understanding the damage from a progressive incremental input motion

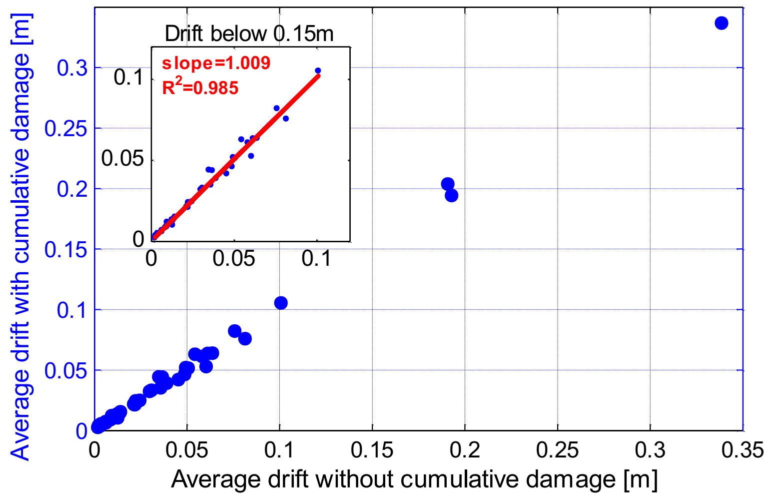
- 16 selected earthquake records with Mw = 6.0 – 6.5 are scaled at 0.2, 0.7, 1.0 and 2.0 factors (4 stages)
- Uni-directional Input motion (transverse and longitudinal)

Case study results:Proposal-1

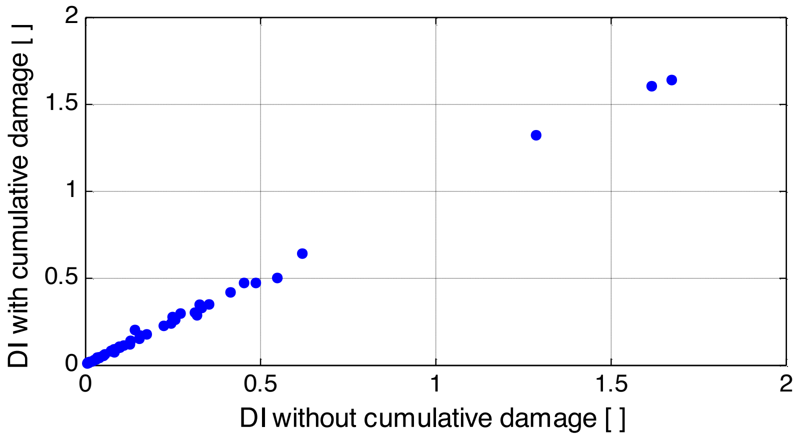
Comparison between progressive testing and independent (IDA) testing:

- Based on parametric analytical analysis apriori





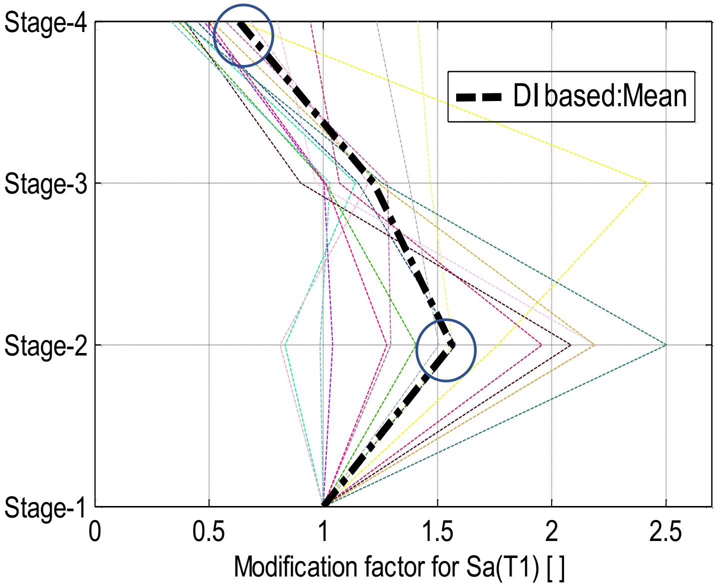
- Negligible damage accumulation is observed in both directions together with small residual displacements
- Collapse damage index are recorded for drifts above the ultimate displacement (estimated via *Fardis et al., 1993*)



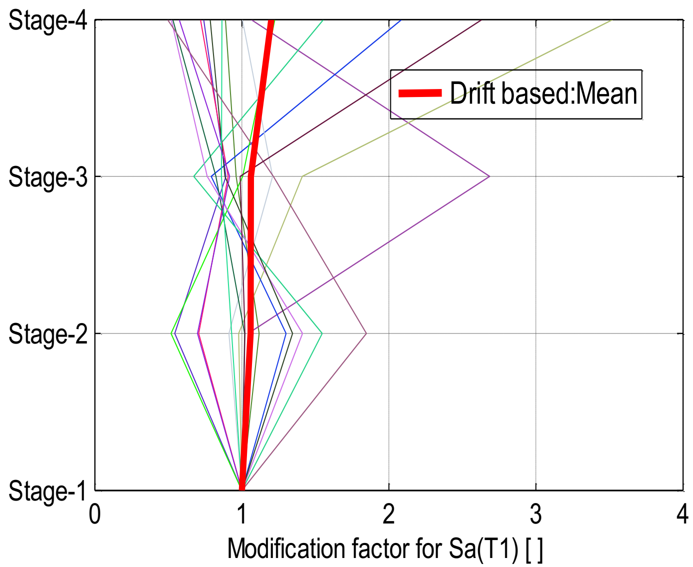
Case study results: Proposal-2

❑ Modification factor based on data from sequential testing

$$\frac{IM_{est,DI}^{stg_i} / Sa(T1)^{stg_i}}{IM_{est.DI}^{stg_{i-1}} / Sa(T1)^{stg_{i-1}}}$$



$$\frac{IM_{est,drift}^{stg_i} / Sa(T1)^{stg_i}}{IM_{est.drift}^{stg_{i-1}} / Sa(T1)^{stg_{i-1}}}$$

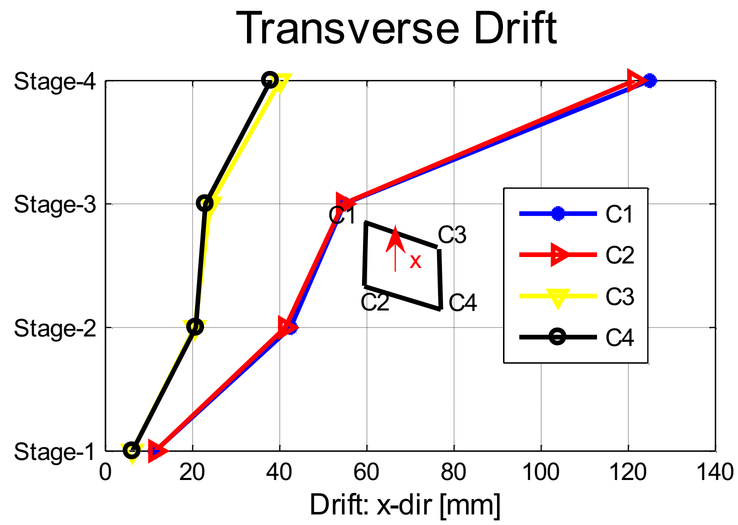


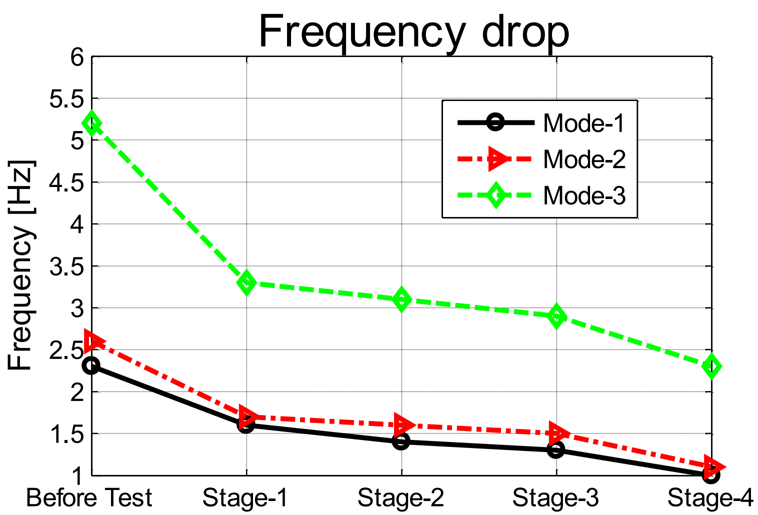
- Proposal-2 based on DI may not be dependable but drift based method can be promising
- Proposed modification factors may need to be investigated further considering a wide range of buildings and earthquake records

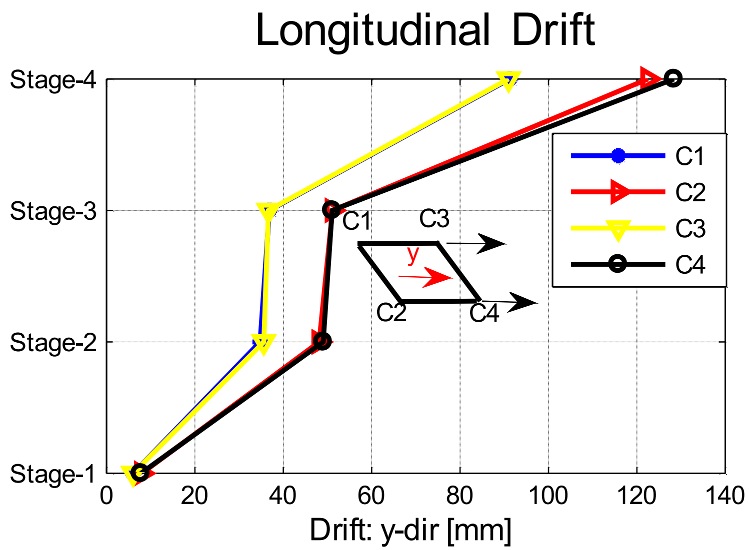
Case study: Experimental/shake table testing

Shake table tests and response:

- Bi-directional input
- Portion of Tohoku unscaled earthquake [Horizontal Components]:
  - PGAx-dir=0.264g; Sa(T1)x-dir=0.489g
  - PGAy-dir:0.253g; Sa(T1)y-dir=0.507g
- 4 stages with factors [0.2, 0.7, 1.0. 2.0]
- Model characterization at the end of each stage of the test





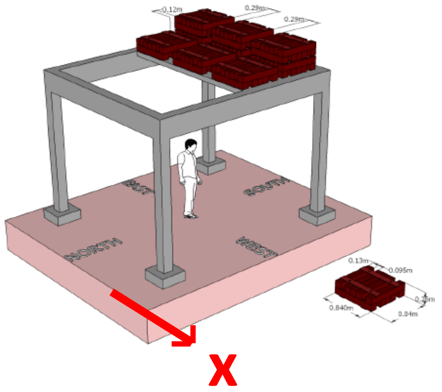


Updating fragility curves via shake table tests

Generation of Fragility curves and updating:

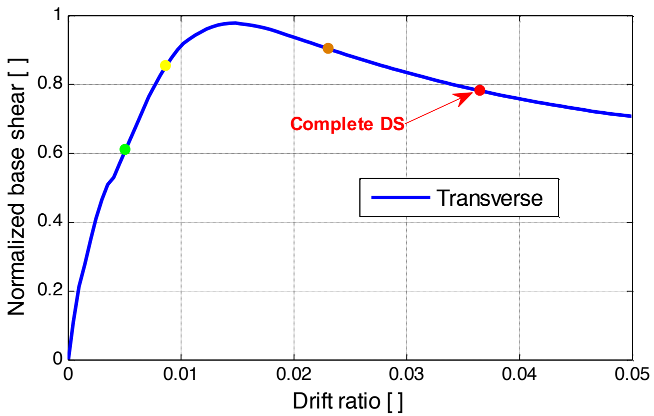
Generated from Incremental dynamic analysis (discussed in slides 11-12)

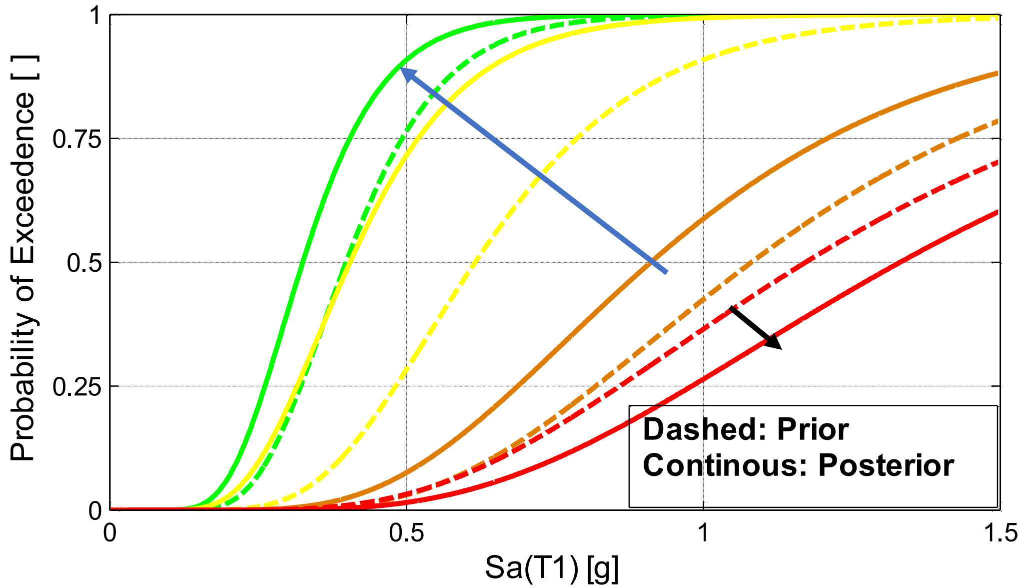
- **HAZUS limit states: Transverse axis**



Damage state	slight	Moderate	Extensive	Complete*
Drift ratio [%]	0.5	0.87	2.33	3.65

Damage state	Slight [Am/β]	Moderate [Am/β]	Extensive [Am/β]	Complete* [Am/β]
Analytical: Prior	0.398g/0.316	0.616g/0.364	1.018g/0.412	1.172g/0.461
Updated: Posterior	0.325g/0.323	0.405g/0.370	0.912g/0.419	1.332g/0.454

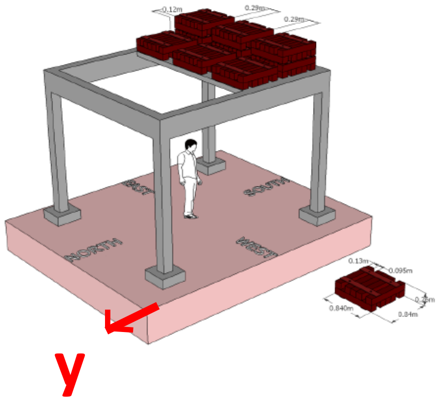




Updating fragility curves via shake table tests

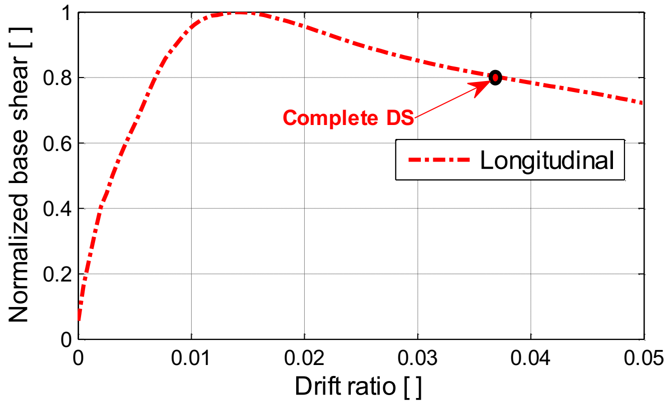
Generation of Fragility curves and updating:

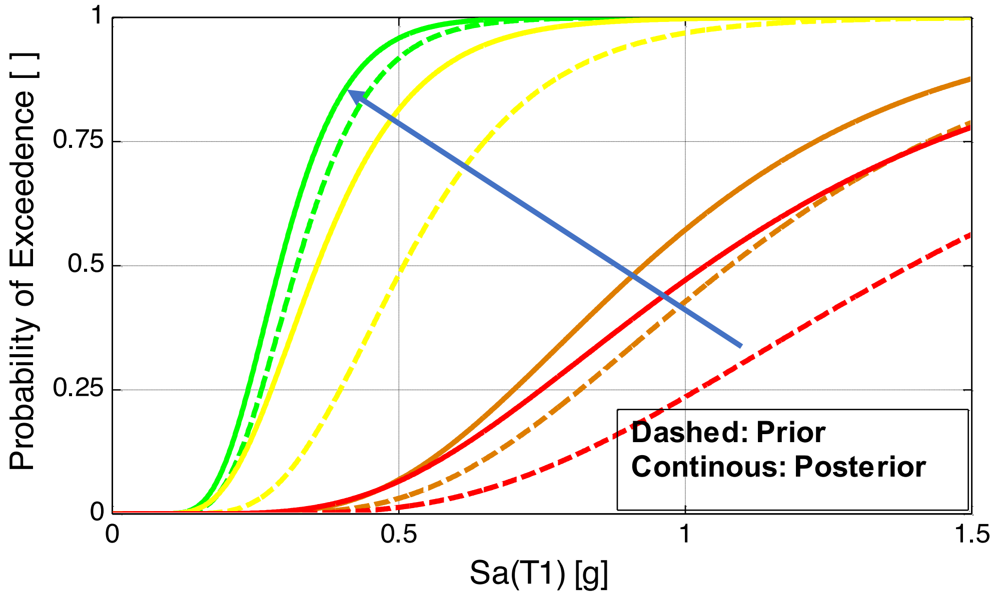
- **HAZUS limit states: Longitudinal axis**



Damage state	slight	Moderate	Extensive	Complete*
Drift ratio [%]	0.5	0.87	2.33	3.65

Damage state	Slight [Am/β]	Moderate [Am/β]	Extensive [Am/β]	Complete* [Am/β]
Analytical: Prior	0.322g/0.316	0.509g/0.364	1.078g/0.412	1.394g/0.461
Updated: Posterior	0.292g/0.311	0.358g/0.375	0.928g/0.416	1.036g/0.482





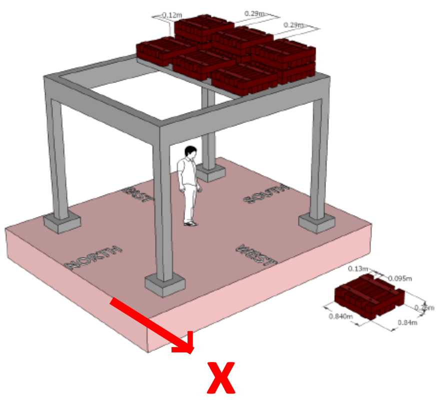
Updating fragility curves via shake table tests

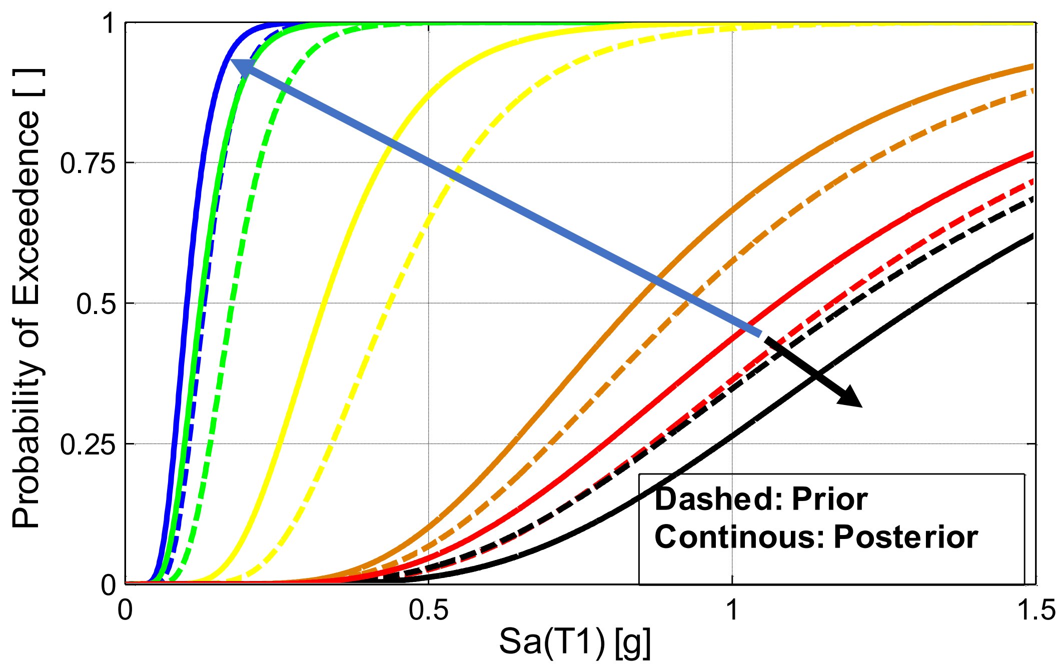
Fragility curves updating based on DS defined through post-earthquake damage:

- **Homogenized RC damage states [Elnashai and Rossetto, 2003]: Transverse axis**

Damage state	light	slight	Moderate	Extensive	p.collpase	Collapse
Drift ratio [%]	0.131	0.189	0.558	1.631	3.341	4.779

Damage state	light [Am/β]	Slight [Am/β]	Moderate [Am/β]	Extensive [Am/β]	P. collapse [Am/β]	Collapse [Am/β]
Analytical: Prior	0.130g/0.316	0.176g/0.340	0.436g/0.364	0.926g/0.412	1.165g/0.437	1.197g/0.461
Updated: Posterior	0.102g/0.332	0.125g/0.355	0.328g/0.375	0.840g/0.408	1.075g/0.456	1.312g/0.430



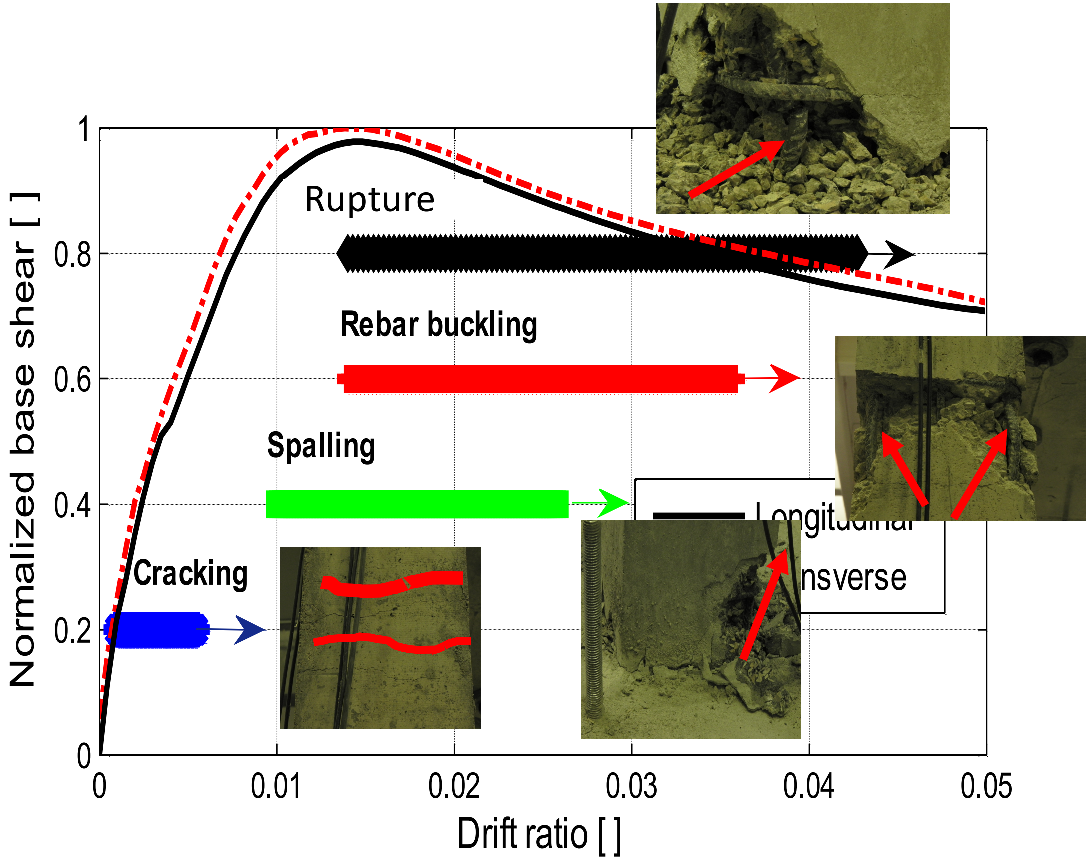


Updating fragility curves via shake table tests

Fragility curves updating based on DS defined for observed damage types:

- **Vision2000 Damage states and *Rodrigues et. al, (2013) findings***

Damage state	Fully operational	Operational	Life safety	Near collapse
Interpreted	cracking	Spalling	Rebar buckling	Rupture
Drift ratio [%]	0.2	0.5	1.5	2.5



DS [Rodrigues et. al, 2013]	Cracking	Concrete spalling	Bar buckling	Steel rupture
Drift ratio [%]	0.1-0.55	1.0-2.6	1.4-3.6	1.4-4.3

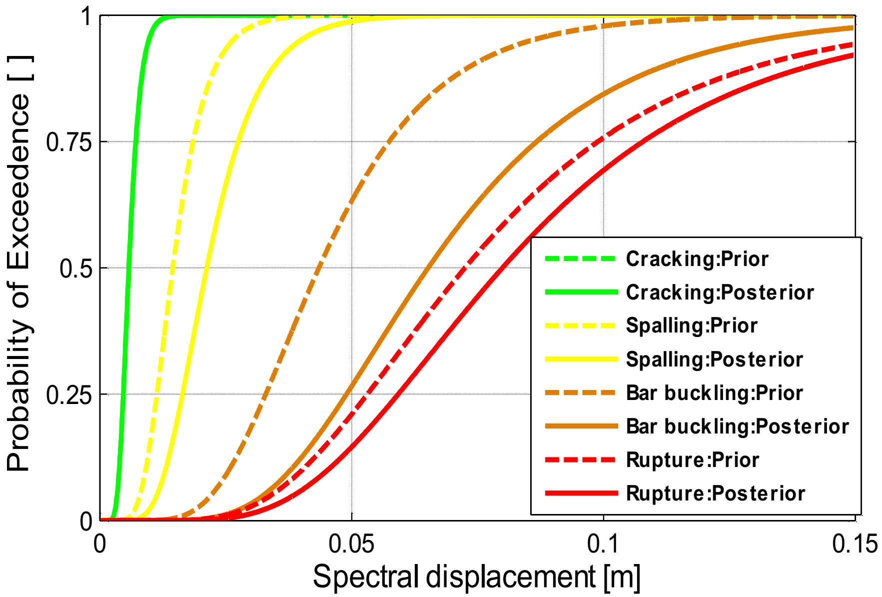
- Resultant drift seems appropriate
- Decision of exceedance was based on true observed data, focusing on columns

Updating fragility curves via shake table tests

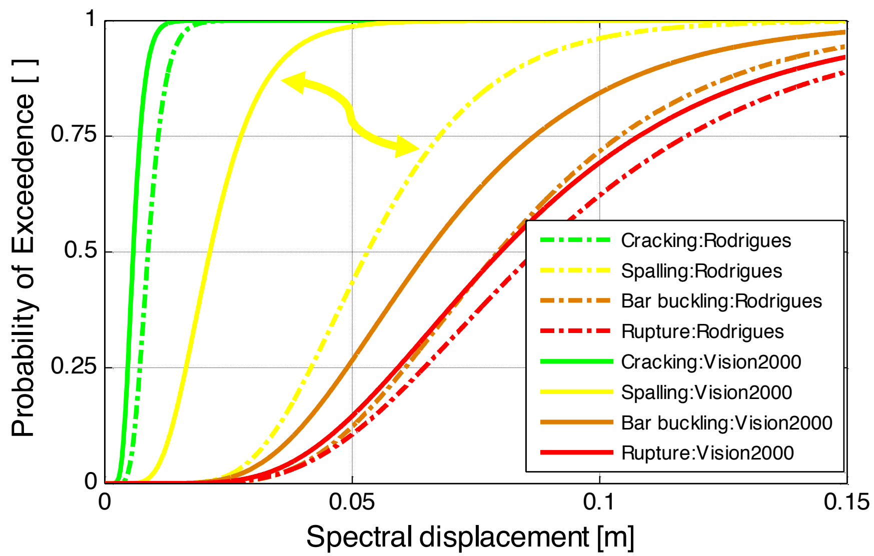
Vision2000 damage states				
Damage state	Cracking [Dm/β]	Spalling [Dm/β]	R.buckling [Dm/β]	Rapture [Dm/β]
Analytical: Prior	5.8mm/0.316	14.5mm/0.364	43.5mm/0.412	72.5mm/0.461
Updated: Posterior	5.75mm/0.316	21.2mm/0.383	65.2mm/0.424	80mm/0.444

Damage states from biaxial RC column cyclic test, Rodrigues et al., 2013				
Damage state	Cracking [Dm/β]	Spalling [Dm/β]	R.buckling [Dm/β]	Rapture [Dm/β]
Analytical: Prior	9.4mm/0.316	52.5mm/0.364	72.5mm/0.412	82.65mm/0.461
Updated: Posterior	8.6mm/0.311	53.1mm/0.358	79.4mm/0.398	87.1mm/0.444

Vision2000: Prior vs updated

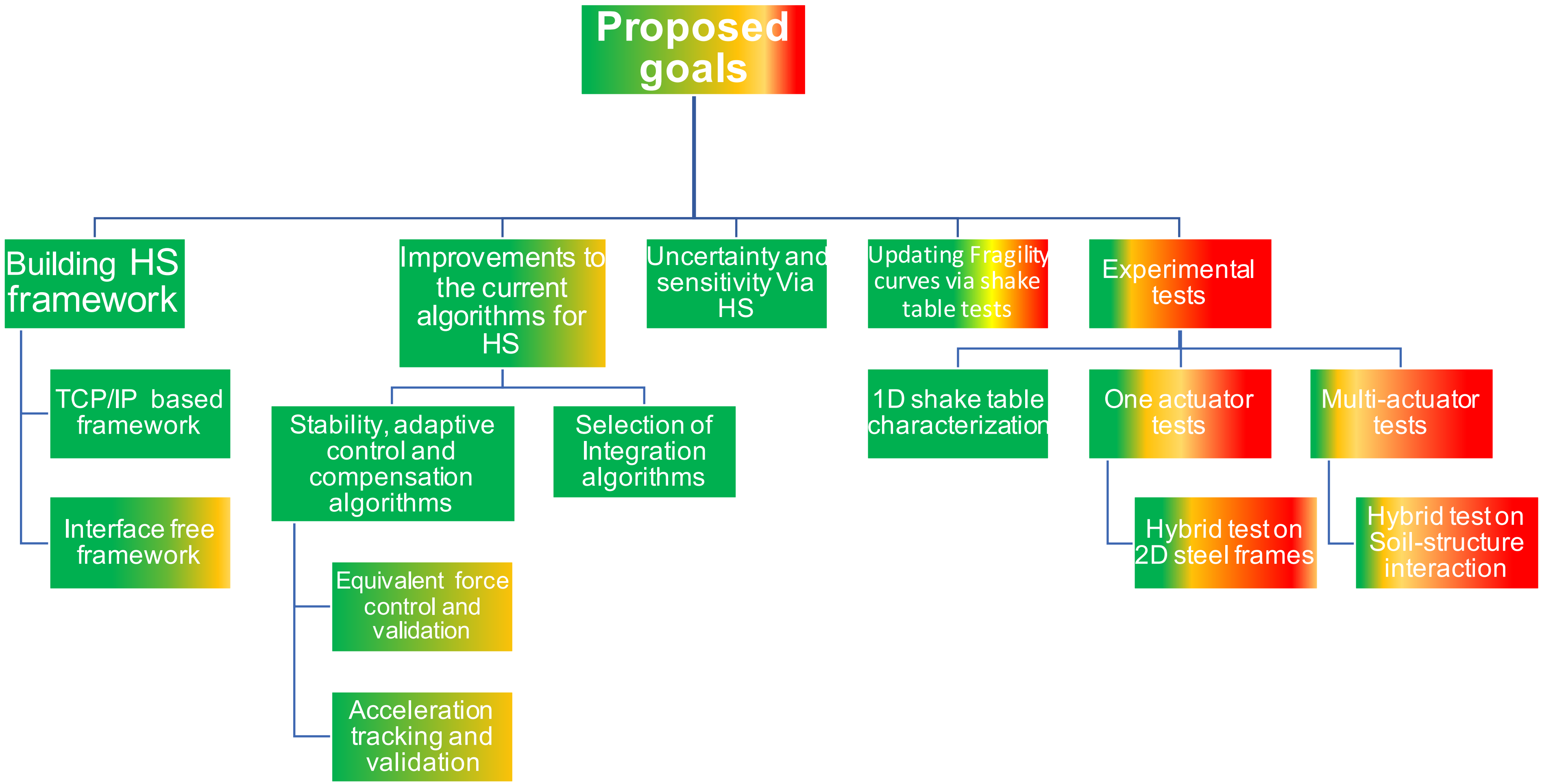


Posterior: Vision2000 vs Rodrigues et al.



Remark: Number of experimental tests may alter the posterior distribution

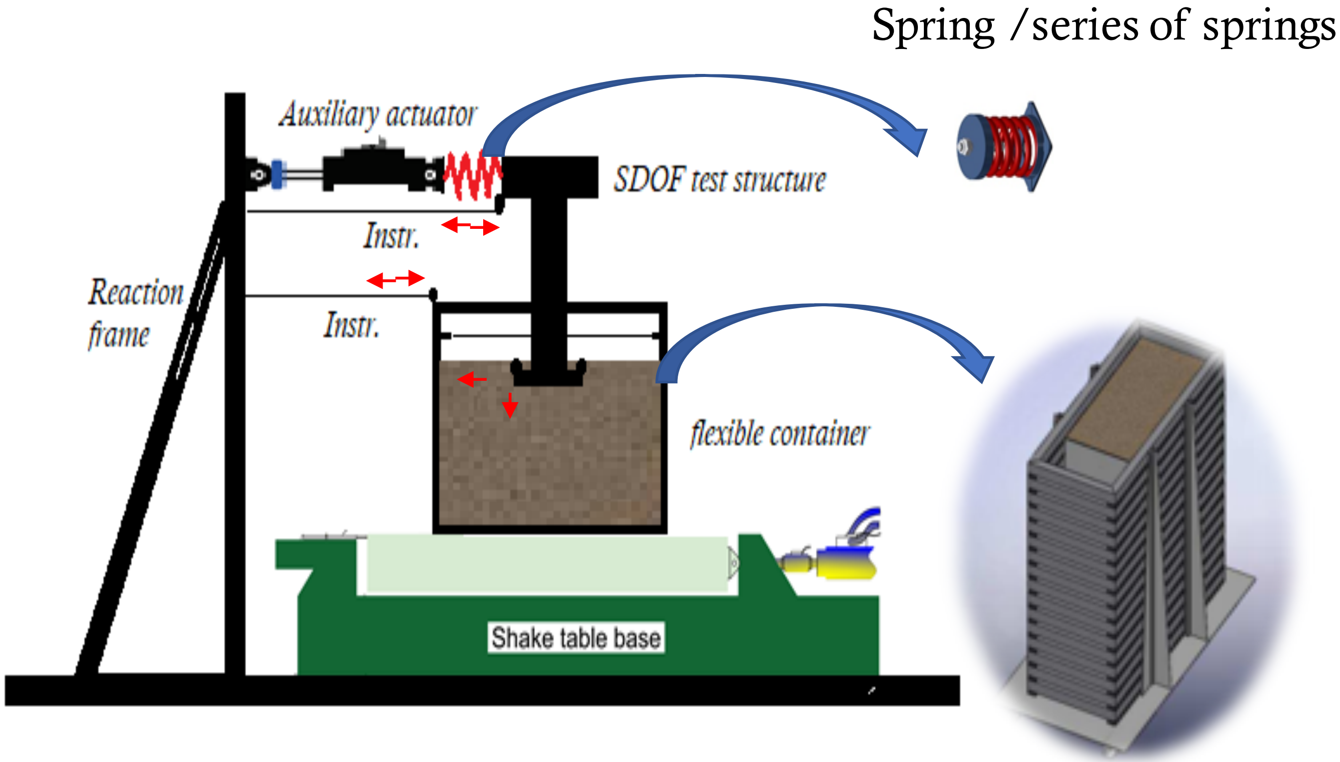
Progress chart



Conclusion

- Experimental test results can only be used to improve fidelity of seismic risk assessment with careful attention
- Modification factor for accounting damage accumulation needs additional investigation under a wide range of earthquake records and structural characteristics, mainly the fundamental frequency and damping properties considering RC buildings only
- A framework for converting observed damage during shake table tests in to damage states defined by codes may be necessary so as to limit the subjectivity of exceedance criteria
- Update based on intensity measure coupled with exceedance decision based on EDP achieved seems a versatile method as opposed to EDP based only method
- Finally, It may be necessary to compare fragility curves built from experimental tests only (to analytically generated fragility curves that are updated by a handful of experimental tests. This might give a sense of validation for the updating technique.
- The fidelity of updating by varying the number of experiments needs be investigated

Plan for SSI testing on HS



- Flexible soil container filled with dry sand: Driven by shake table
- Lower story of a structure (that makes part of a multi-story reference frame): Erected on the sand deposit and loaded by an auxiliary actuator
- Shake table with acceleration tracking control property
- Auxiliary actuator with added compliance based equivalent force control

Thank you for your attention!

gtekeste@lnec.pt