Quantifying fragility functions for non-ductile infilled RC buildings from past earthquakes: analytical models versus empirical data

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Centre for Training and Research on Reduction of Seismic Risk

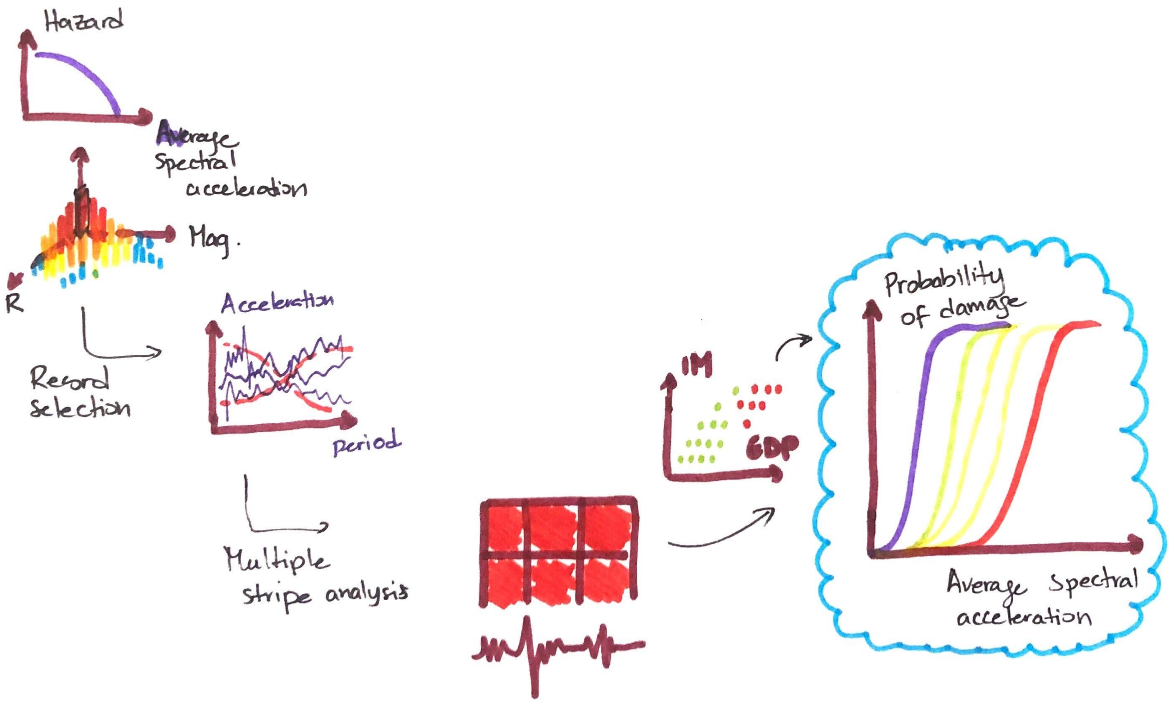
Introduction

- Infilled RC buildings occupy a significant portion of the regional building stock
- The majority of Italian RC buildings were constructed before the introduction of modern seismic codes:
  - Before 1970s: Gravity loads (GLDs)
  - 1970s – 1980s: ELF method (SSDs)
  - URM panels were considered as non-structural elements
- Post-earthquake reports highlighted the vulnerability of the existing regional building stock to ground-shaking events

Joint Reconnaissance EUCENTRE-ReLUIS, Turkey-Syria Earthquake 2023 - Final report

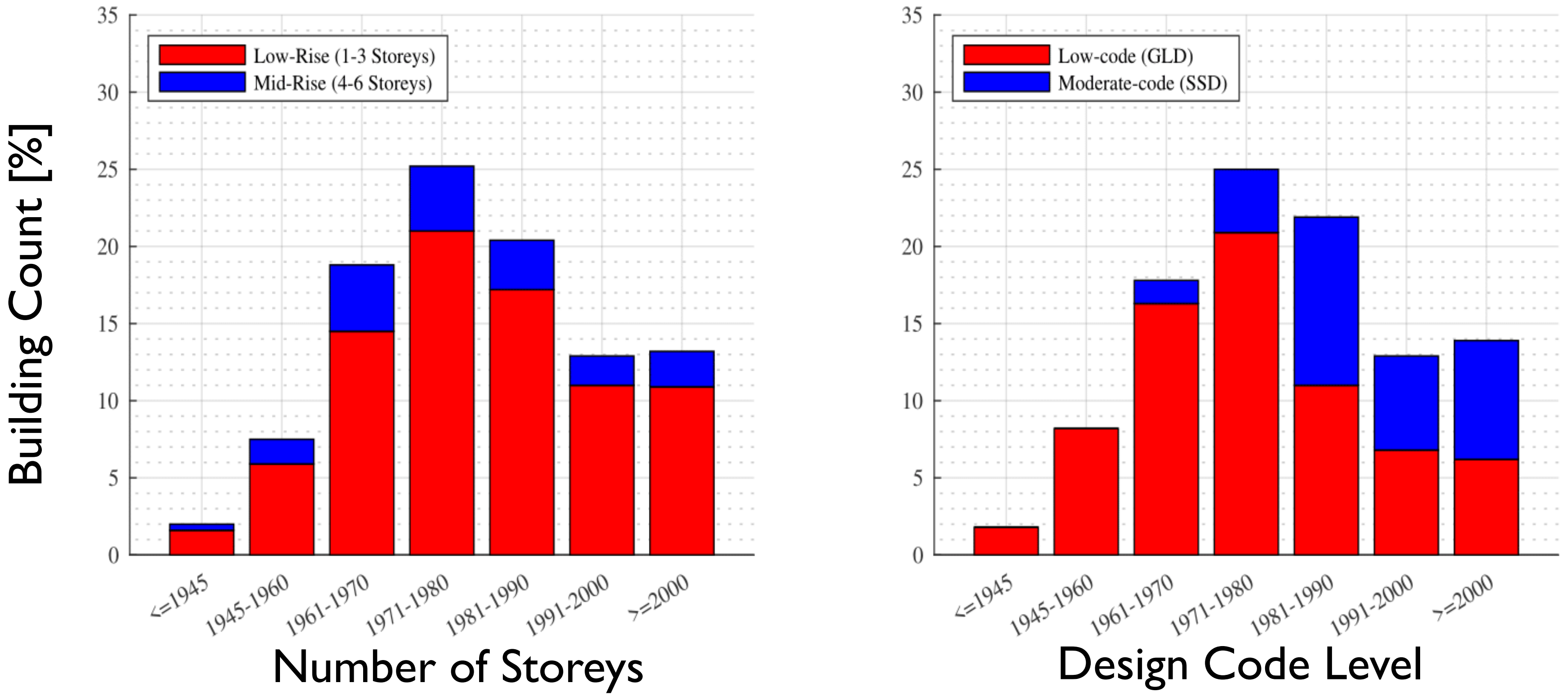
Motivation

- Common practice to develop fragility functions **analytically**
- Use state of the art tools in hazard analysis, ground motion selection, numerical modelling and analysis
- Much data has been collected following several earthquake events around the world
- This can be elaborated into **empirical** fragility functions
- How well are we doing when:
  - We compare empirical vs. fragility
  - Integrate recent research developments in fragility analysis



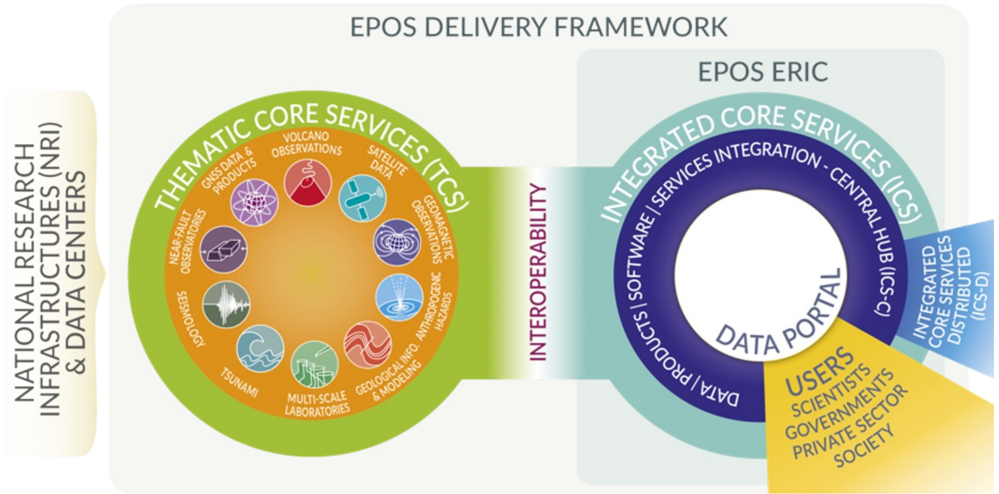
Definition of Building Classes

- The definition of a building class is a key step towards assessing seismic risk.
- Building classes must be defined using building attributes relevant to seismic vulnerability

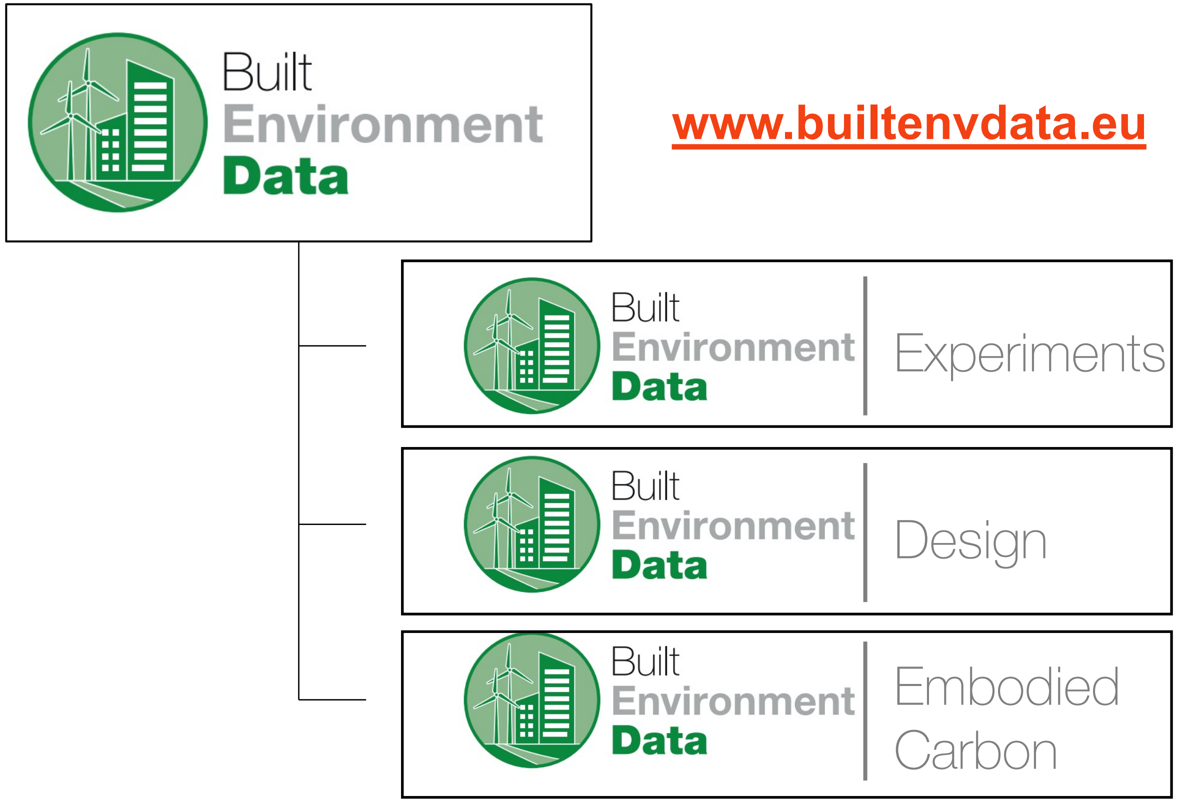


Simulated Design Framework

- As part of a recent initiative to create an EPOS Thematic Core Service, the Built Environment Data service is under construction



- It aims to provide access to data and services related to the built environment
- One of these services related to simulated designs



www.builtenvdata.eu

Simulated Design Framework

Design Class

CDN: no seismic design (i.e., the building codes for gravity design only)

- before 1960’s

CDL: low ductility (i.e., the first generation of seismic codes)

- 1960s to 1970s
- Introduction of seismic loads

CDM: moderate ductility (i.e., the second generation of seismic design codes)

- 1970s to 2000s
- Introduction of partial safety factors

CDH: high ductility (i.e., the third generation of seismic design codes)

- 2000s to present
- Introduction of q factor and capacity design

Number of storeys

Design Lateral Force Coefficient

Seismic design is based on a lateral force coefficient, β (**i.e., the fraction of the weight of the building defining the lateral force**)

$$\beta = K_s \cdot K_o \cdot K_d \cdot K_p$$

K_s: coefficient based on seismic intensity
K_o: coefficient based on the type/importance of the building

K_d: coefficient that accounts for dynamic response (e.g., lambda factor of EC8-1 section 4.3.3.2.2)

K_p: coefficient that accounts for ductility and energy dissipation

Number of Buildings

Ratio of Buildings with Specific Construction Quality

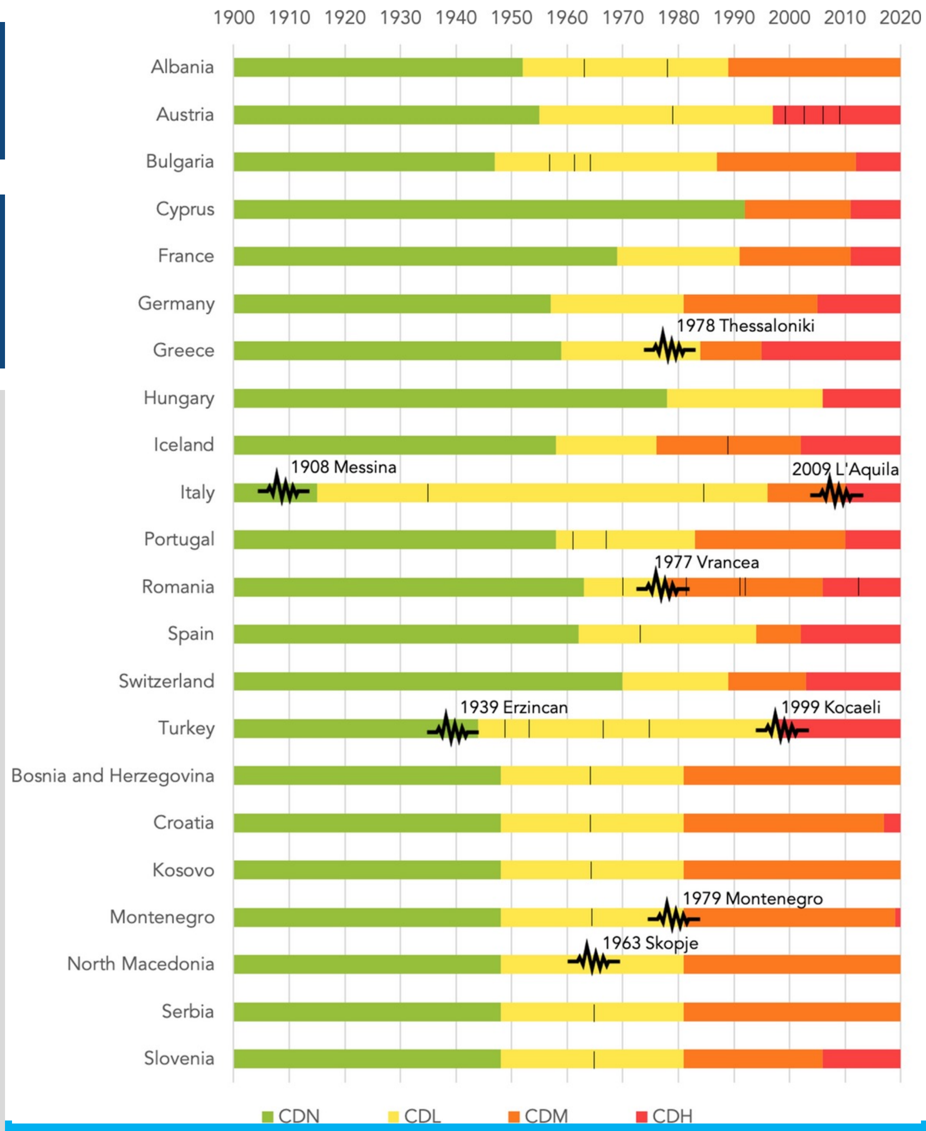
Accounts for compliance with code enforcement**. Quality factors** are categorized as:

- Good
- Moderate
- Bad

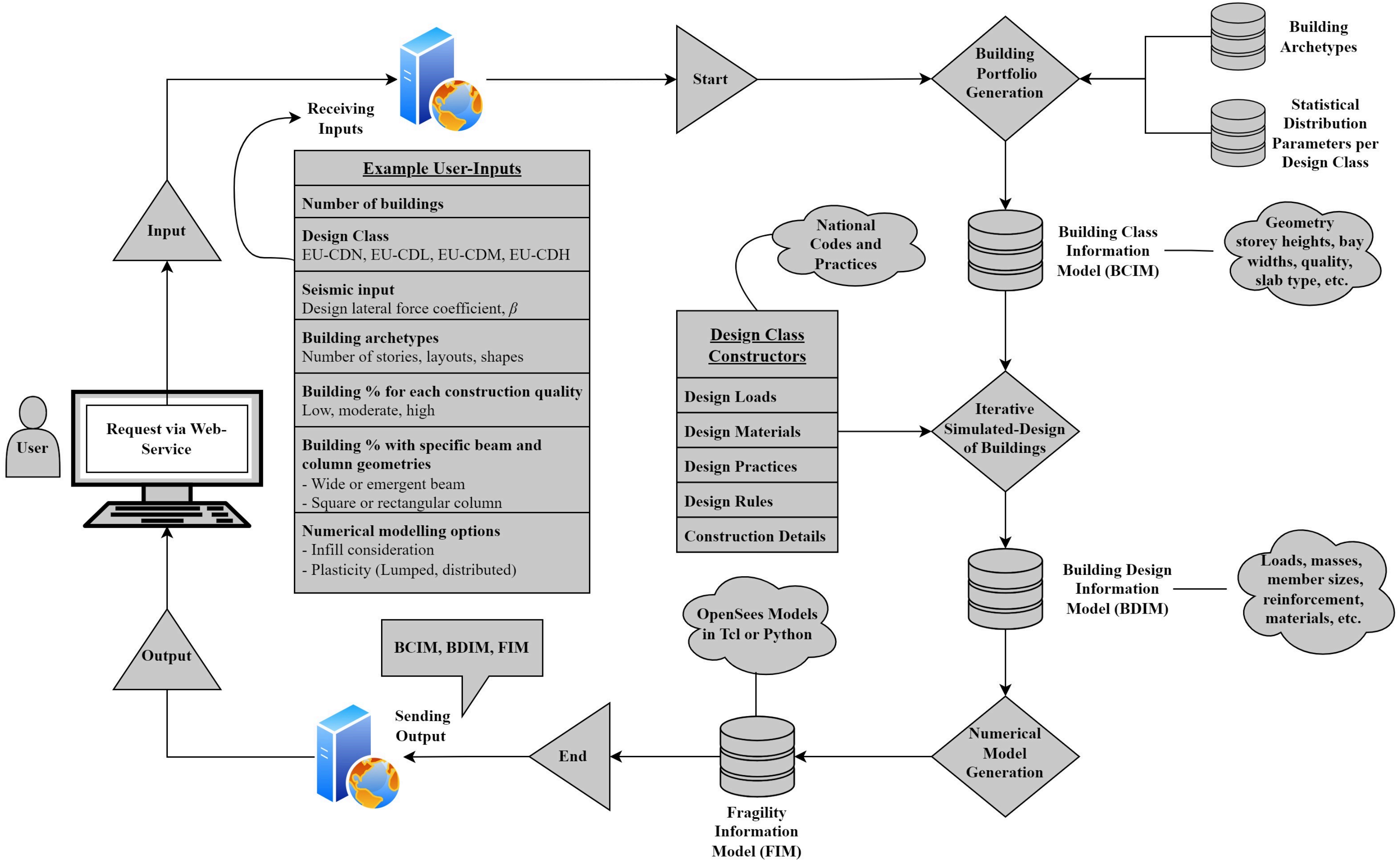
Implementation in **numerical models** involves modifying design values for the followings:

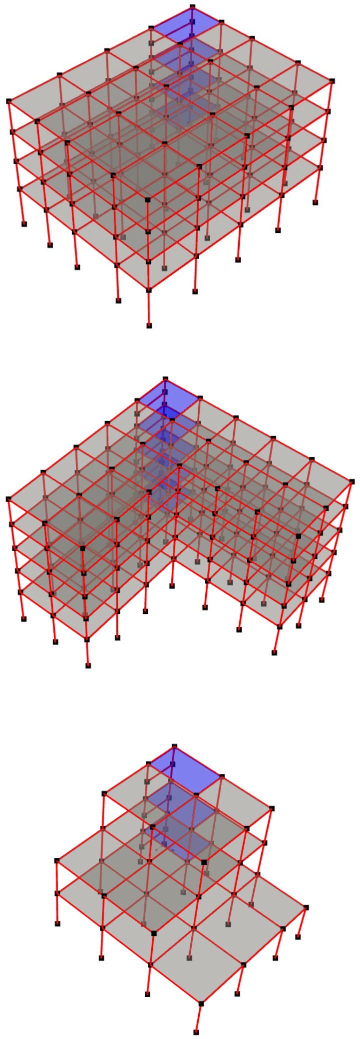
- Stirrup spacing
- Concrete cover
- Concrete strength
- Steel yield strength of reinforcement

Along with design class, it alters **joint modelling** approach and **the bond slip-factor** in numerical models



Simulated Design Framework

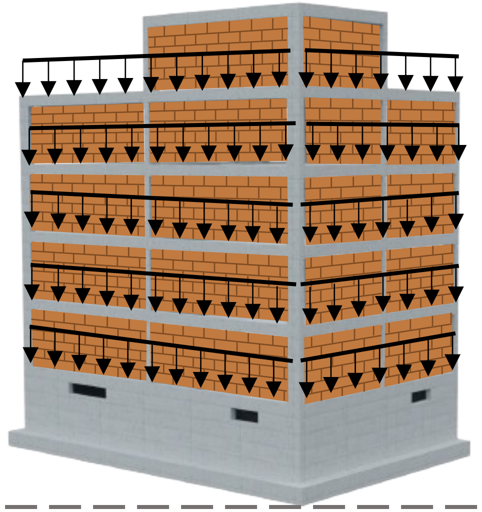




Database of Archetype Numerical Models

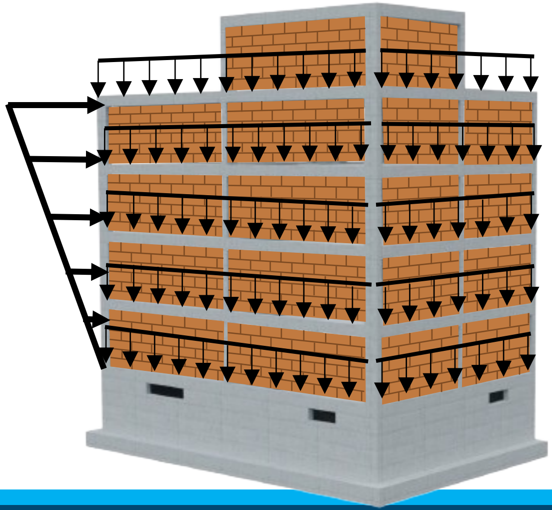
- Design space considerations through identification of the geographic construction practice

Pre-1970s
(GLD)



- Gravity loads only
- Allowable stress method (RD 2229/39)
- Smooth rebars with a low yield strength (≈ 325 MPa)
- Concrete with low compressive strength (≈ 25 MPa)
- Low shear reinforcement ratios
- Inadequate detailing of beam-column joints
- Frames spanning in one direction

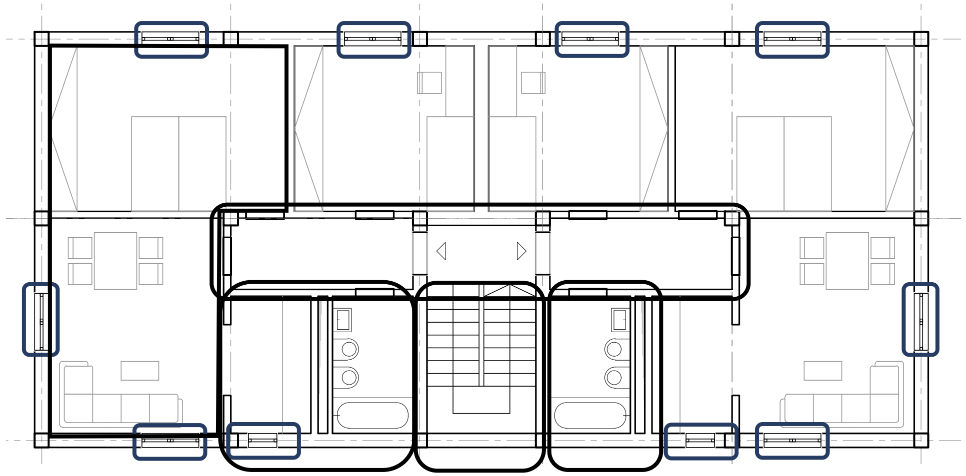
- ELF method (Seismic coefficient 5-10%)
- Allowable stress method
- Deformed rebars with typical yield strength (≈ 430 MPa)
- Concrete with moderate compressive strength (≈ 28 MPa)
- Low shear reinforcement ratios
- Frames spanning in one (or both) direction



1970s-1980s
(SSD)

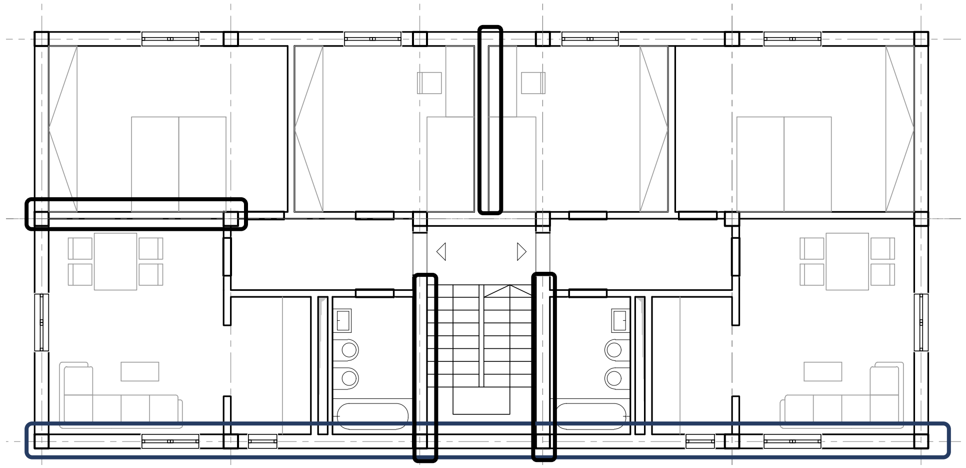
Database of Archetype Numerical Models

- Geometric configuration and architectural features selected to reflect the function and form of the Italian design space over different building periods
- Expert architectural judgment following numerous consultations with practitioners and architects
- Features include:
  - Narrow hallways and corridors in dwellings, generally 150 cm wide
  - Adjacent kitchens and bathrooms
  - Plumbing fixtures (e.g. bathtubs, sinks and bidets) installed based on optimized space allocation
  - Adequate separation of the day and night living spaces
  - Windows with widths in multiples of 45 or 60 cm
  - Staircase width not exceeding 3 m (i.e. wide enough to allow the passage of two people) and landings depth not exceeding 1.3 m



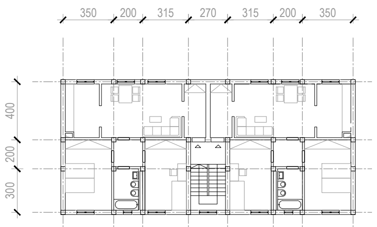
Database of Archetype Numerical Models

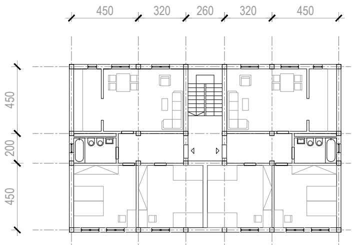
- Geometric configuration and architectural features selected to reflect the function and form of the Italian design space over different building periods
- Expert architectural judgment following numerous consultation with practitioners and architects
- Features include:
    - Double-leaf masonry infills for thermal and acoustic insulation and fire-retarding
    - 24 cm infill panels for perimeter walls of the façade
    - 30 cm infill panels for the separation of dwellings and encasing of the staircase
    - 80 mm single-leaf masonry infills for Internal partitioning

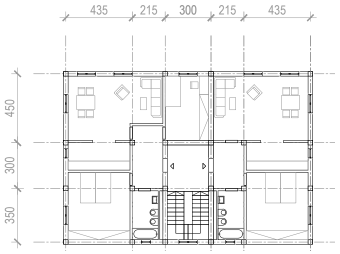


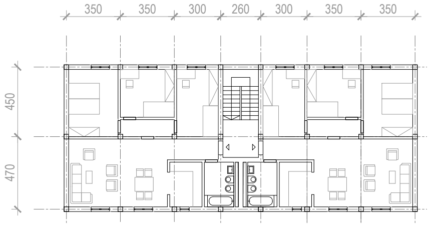
Database of Archetype Numerical Models

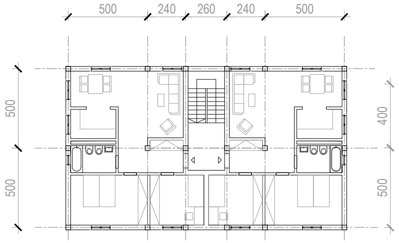
Architectural Layouts


Archetype A

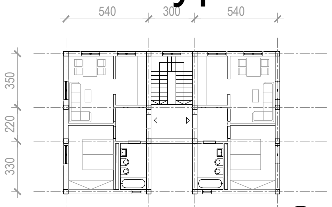

Archetype B


Archetype C

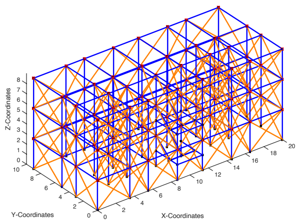

Archetype D

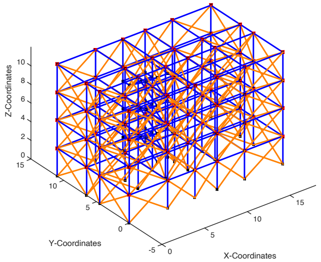

Archetype E

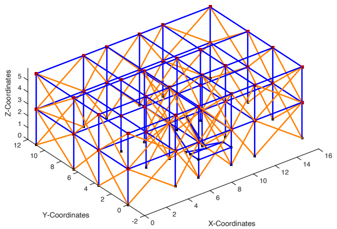

Archetype F

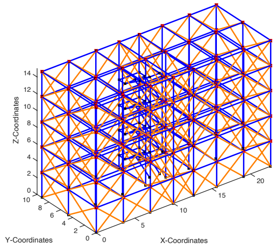

Archetype G

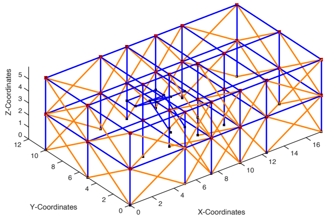
Numerical Models

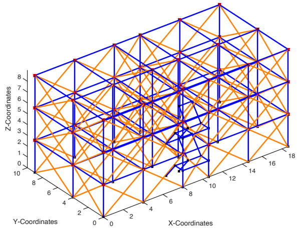

Archetype A

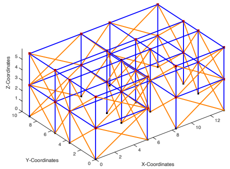

Archetype B


Archetype C


Archetype D


Archetype E


Archetype F


Archetype G

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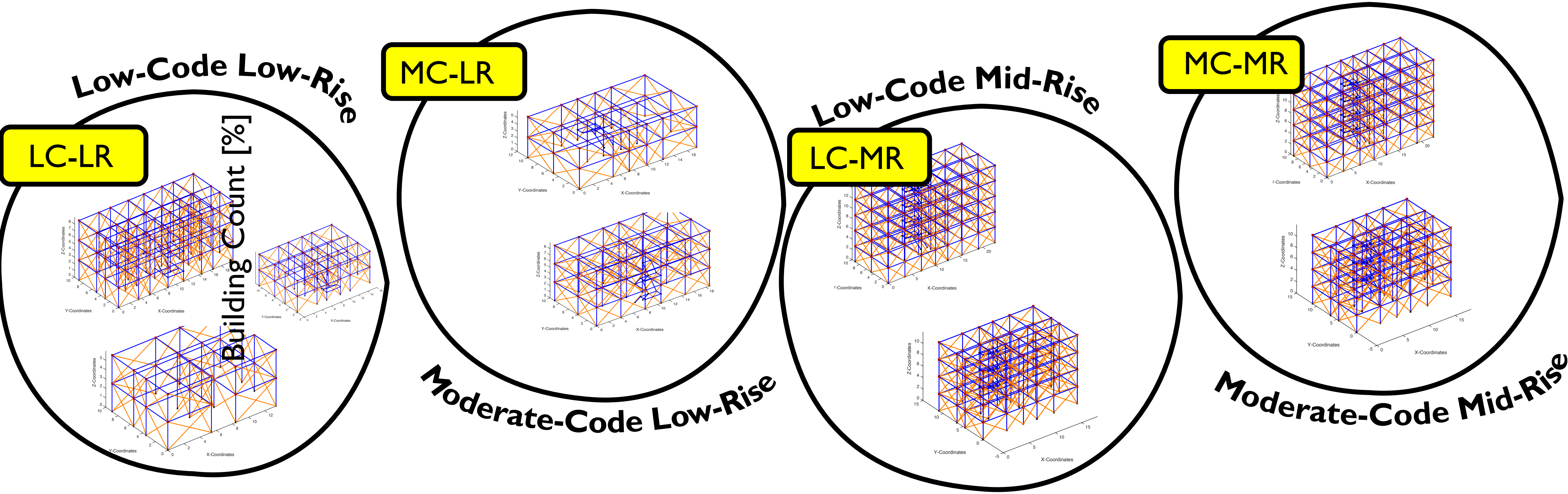
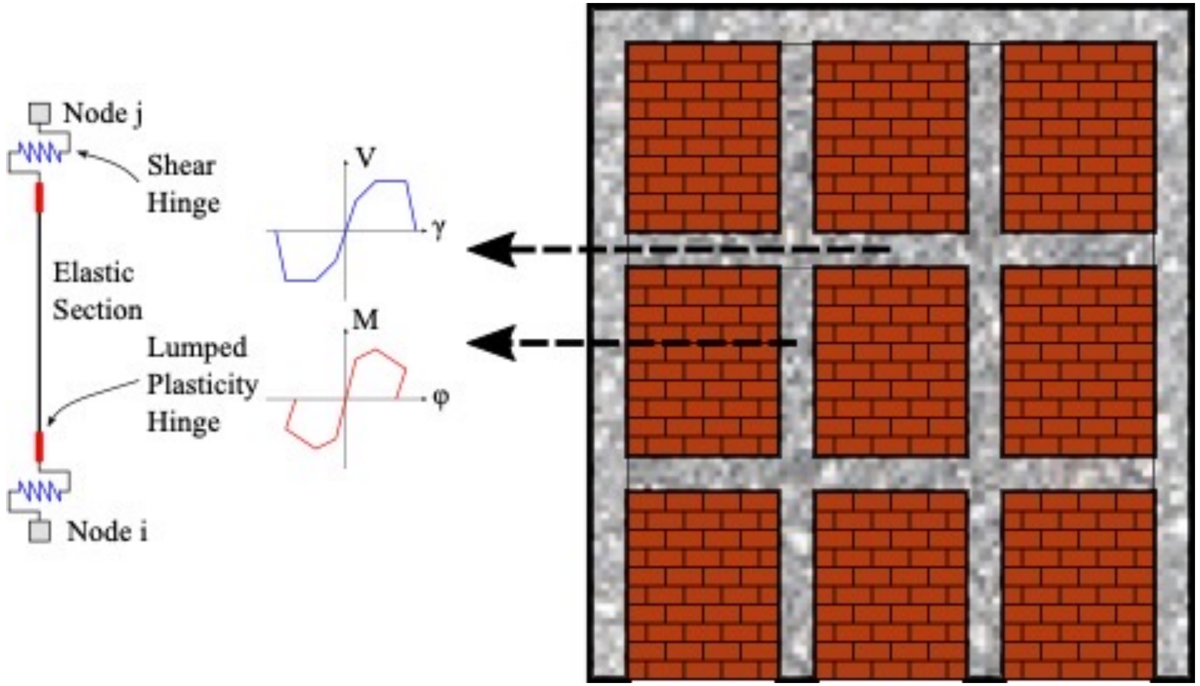


Numerical Modelling of Buildings (Beam-Column Elements)

- Lumped hinge beam-column element to describe the flexural behaviour
    - “forceBeamColumn” elements with a finite plastic hinge length
    - “Pinching4” hysteretic material model based on the force-deformation relationships for non-conforming structures

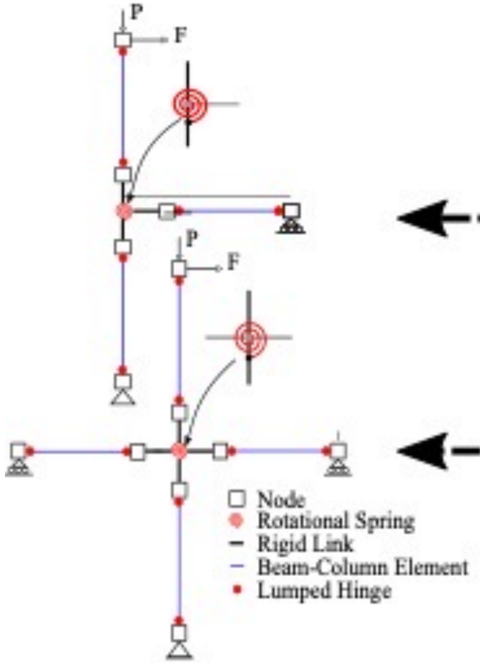
- Together in series with an aggregated shear hinge that allows for the uncoupled shear response of the member

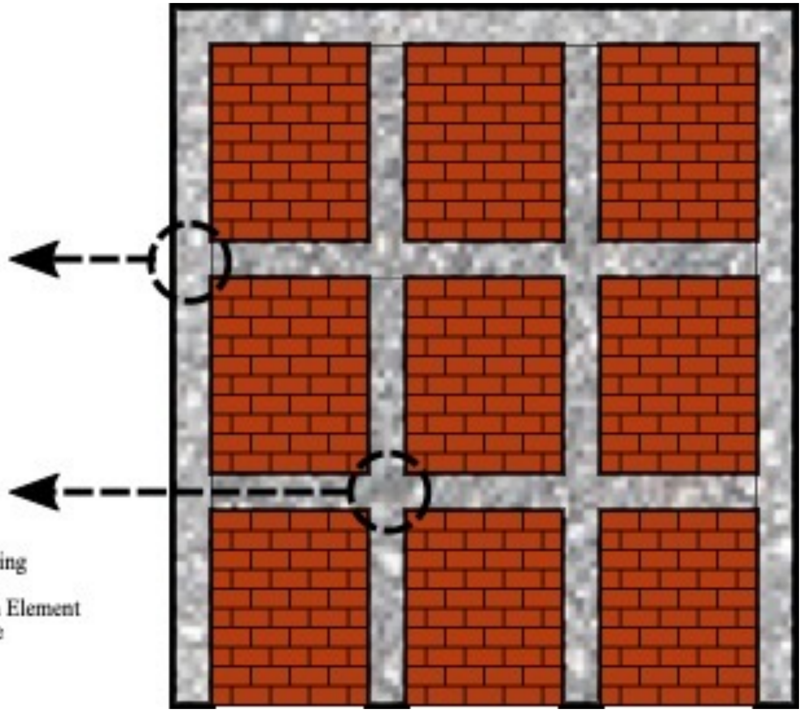


- *Verderame GM, Ricci P, De Risi MT, Del Gaudio C. Experimental Assessment and Numerical Modelling of Conforming and Non-Conforming RC Frames with and without Infills*
- *O’Reilly GJ, Sullivan TJ. Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures. J Earthq Eng 2019*

Numerical Modelling of Buildings (Beam-Column Joints)

- Proposed model layout for interior and exterior beam-column joints using rotational springs linking the vertical and horizontal rigid links in a ”Scissors Models”
- zero-length elements using a “Hysteretic” model elements to capture both flexural and axial behaviour
- Rigid-links offsets and lumped rotational spring for the shear deformation of the joint region
- Limit states determined through experimental observations, expressed as a function of the concrete tensile strength

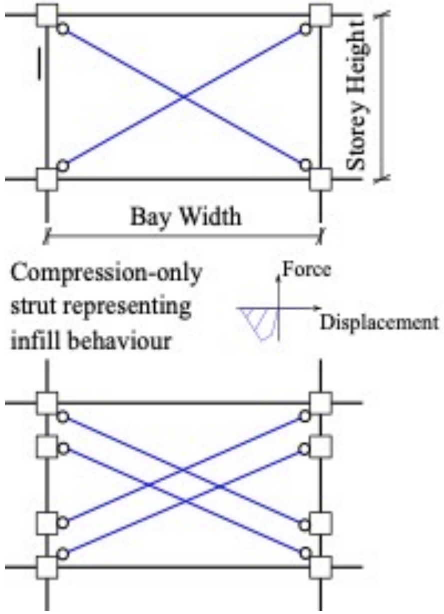


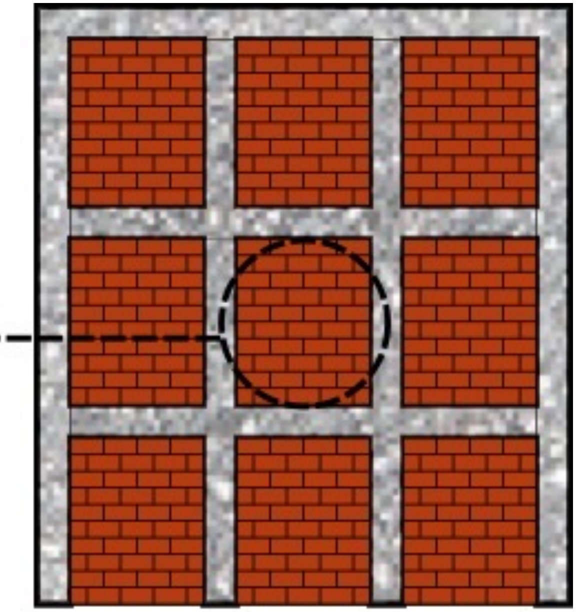


- *O’Reilly GJ, Sullivan TJ. Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures. J Earthq Eng*
- *De Risi MT, Verderame GM. Experimental assessment and numerical modelling of exterior non- conforming beam-column joints with plain bars. Eng Struct*

Numerical Modelling of Buildings (Masonry Infills)

- Various equivalent diagonal strut modelling approaches
- In-plane behaviour modelled using the equivalent strut approach
- Compression-only single/double strut models
- Further improvements foresee the inclusion of an IP-OOP interaction modelling

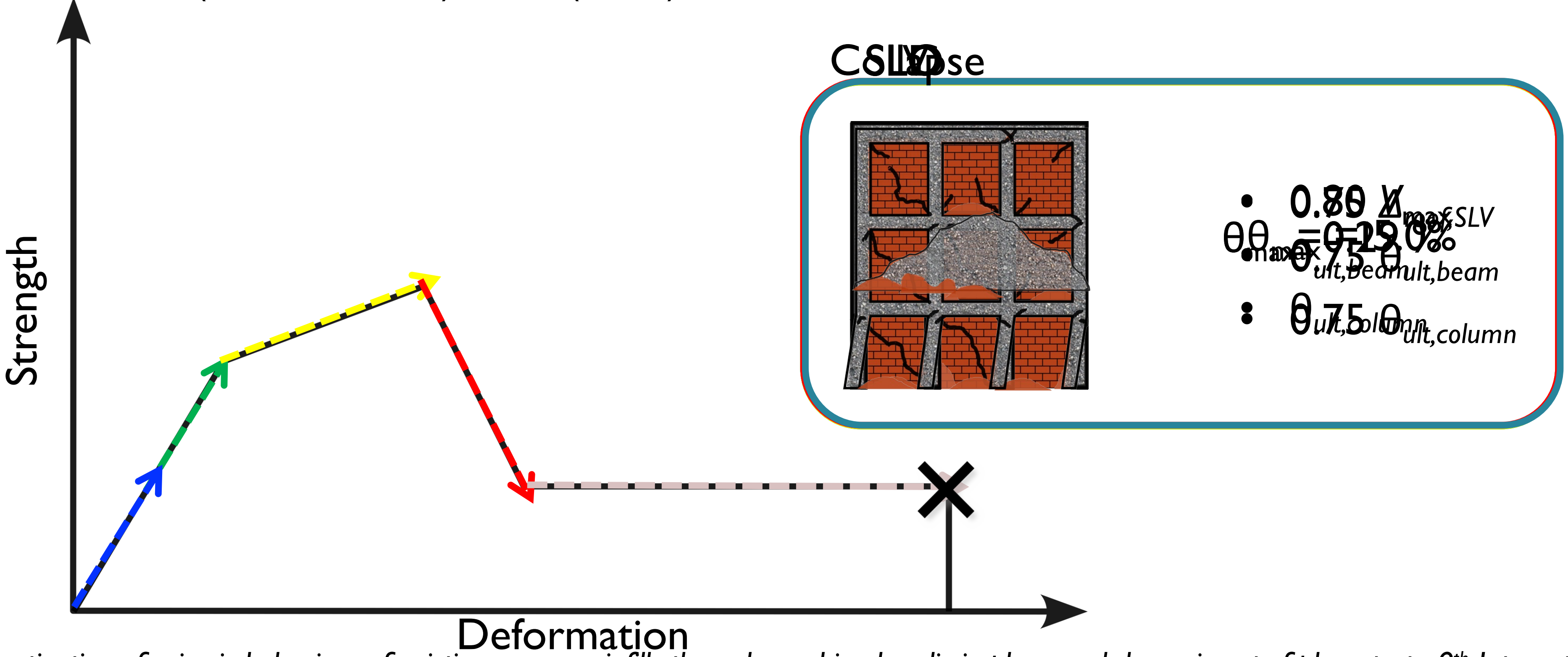




- *O'Reilly GJ, Sullivan TJ. Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures. J Earthq Eng 2019*
- *Hak S, Morandi P, Magenes G, Sullivan TJ. Damage control for clay masonry infills in the design of RC frame structures. J Earthq Eng 2012*
- *Crisafulli, F. J., Carr, A. J., Park, R. [2000] "Analytical Modelling of Infilled Frame Structures - A General Review," Bulletin of the New Zealand Society for Earthquake Engineering*
- *Milanesi, R. R., Morandi, P., Hak, S., & Magenes, G. (2021). Experiment-based out-of-plane resistance of strong masonry infills for codified applications. Engineering Structures*
- *Morandi, P., Hak, S., Milanesi, R. R., & Magenes, G. (2022). In-plane/out-of-plane interaction of strong masonry infills: From cyclic tests to out-of-plane verifications. Earthquake Engineering & Structural Dynamics*

Definition of DSs Thresholds

- A hybrid definition of the damage state thresholds was considered
  - Serviceability Limit States (SLO and SLD): Kurukulasuriya *et al.* (2022)
  - Ultimate Limit States (SLV and SLC): NTC (2018)



- *Kurukulasuriya et al. (2022) Investigation of seismic behaviour of existing masonry infills through combined cyclic in-plane and dynamic out-of-plane tests, 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Methods in Structural Dynamics and Earthquake Engineering*

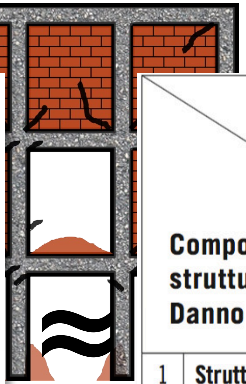
Analytical-Empirical DS Harmonisation

Quantitative Damage States

Norme Tecniche Per Le Costruzioni (2018)

Qualitative Damage States

Agibilità e Danno nell' Emergenza Sismica

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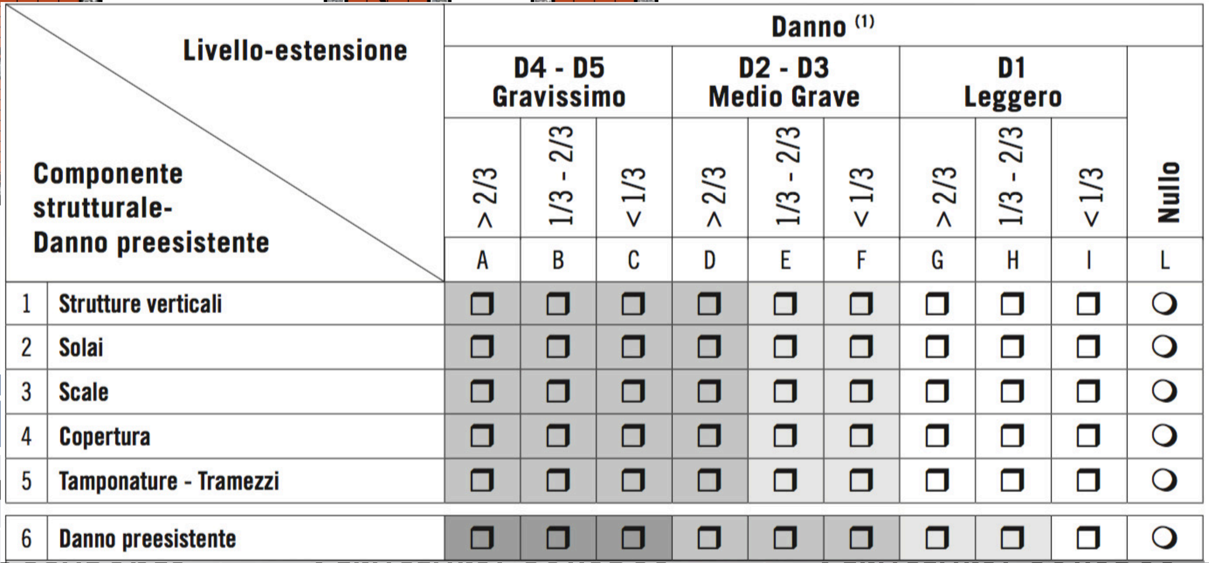


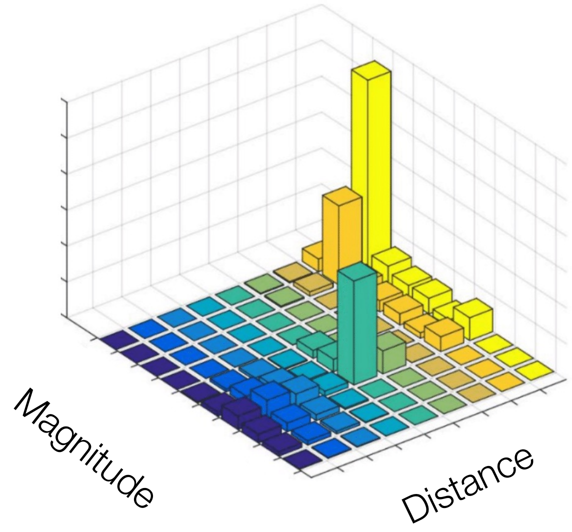
Livello-estensione / Componente strutturale-Danno preesistente	Danno [1] D4 - D5 Gravissimo			D2 - D3 Medio Grave			D1 Leggero			Nullo
	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
	A	B	C	D	E	F	G	H	I	L
1 Strutture verticali	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍
2 Solai	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍
3 Scale	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍
4 Copertura	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍
5 Tamponature - Tramezzi	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍
6 Danno preesistente	❐	❐	❐	❐	❐	❐	❐	❐	❐	❍

		SLV		
		D2-D		
Functionality and usability of the building	Safety and immediate occupancy	Protection of occupants lives and ensurance of safe evacuation	Structural collapse prevention	Structural collapse

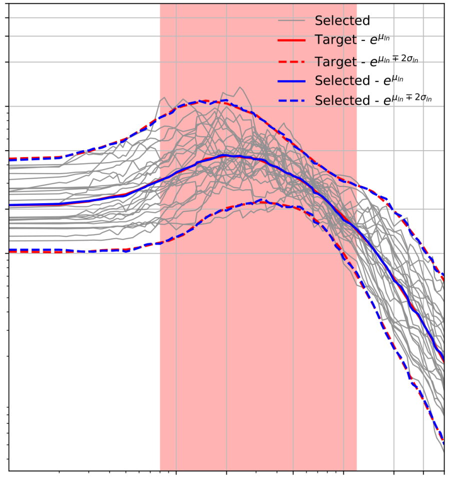
Seismic Performance Assessment

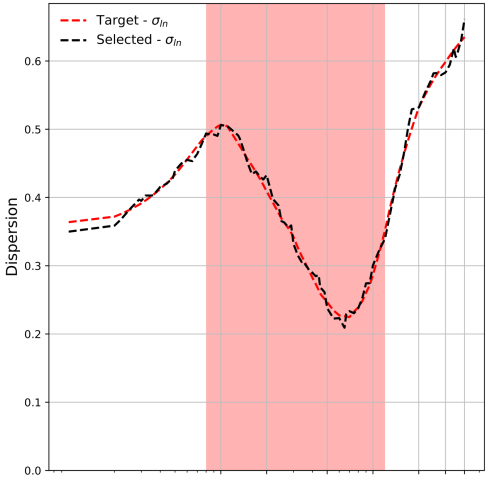
- NTLHA method: Multiple-stripe analyses
- Hazard-consistent ground-motion records selected using the Djura Record Selector
- Nine intensity measure levels corresponding to return periods of 22-4975 years
- Scaling factor threshold of 2.0
- Structural response was characterised in terms of the maximum peak storey drift (θ_{max})
- A drawback of MSA for this application is that each archetype building model was evaluated using a slightly different definition of $Sa_{avg}(T^*)$

PSHA and disaggregation



Ground motion selection





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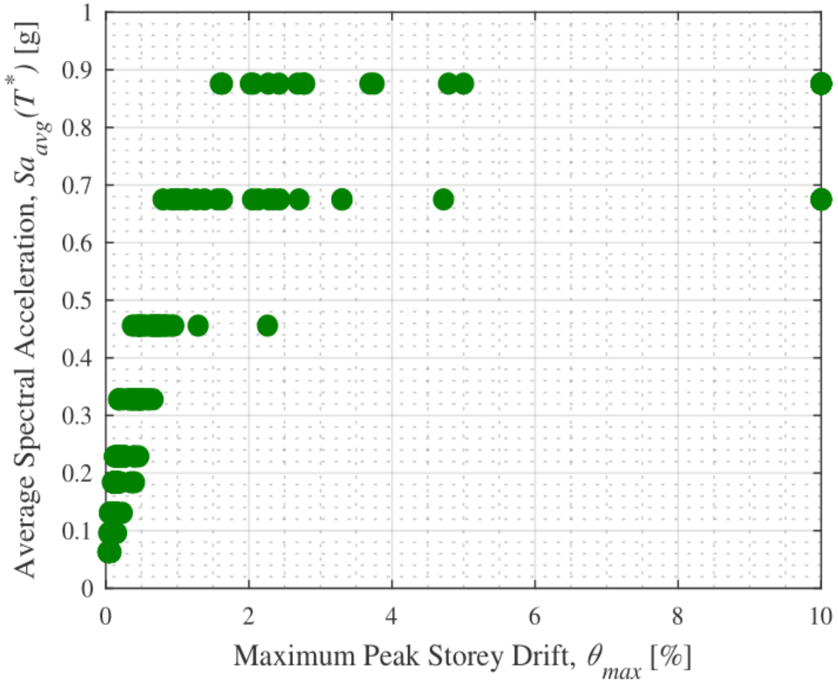


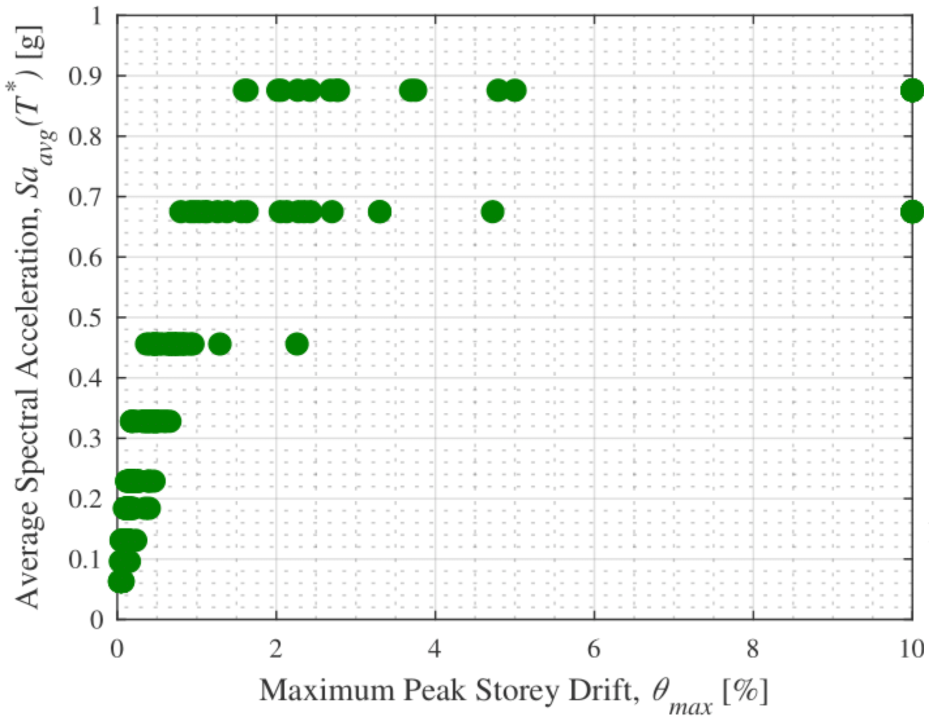
Multiple-stripe analysis results of

a case study building

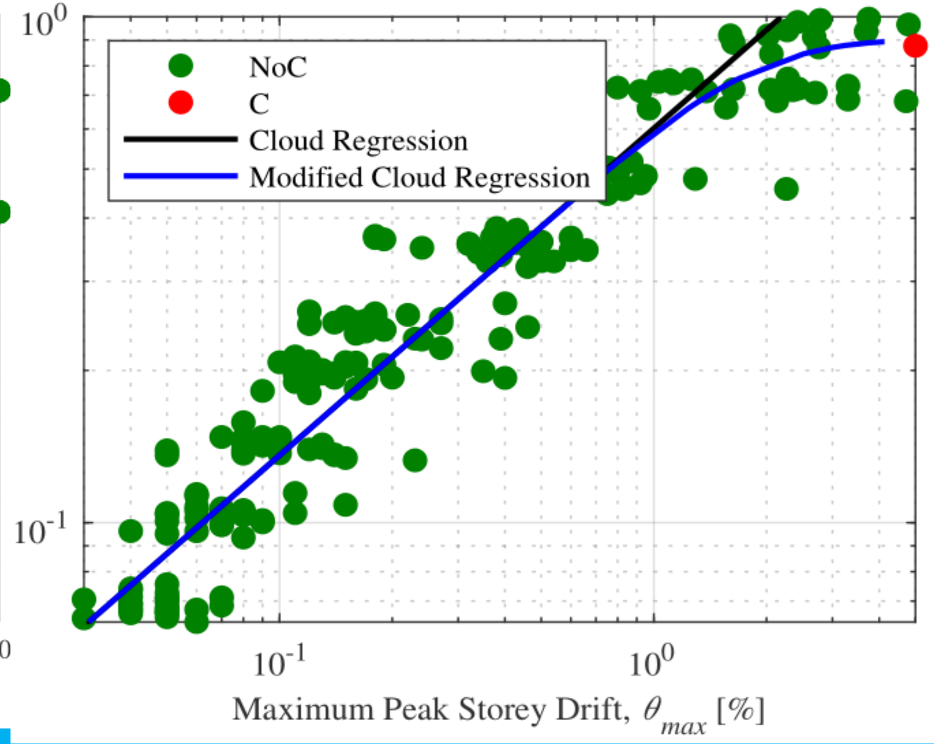
Seismic Performance Assessment

- Due to building grouping, MSA results transform into a “banded cloud” of results
- Results remain hazard-consistent
- A more direct approach is to directly select ground-motion records for MSA in terms of $Sa_{avg}(T^*_{tax})$

MSA

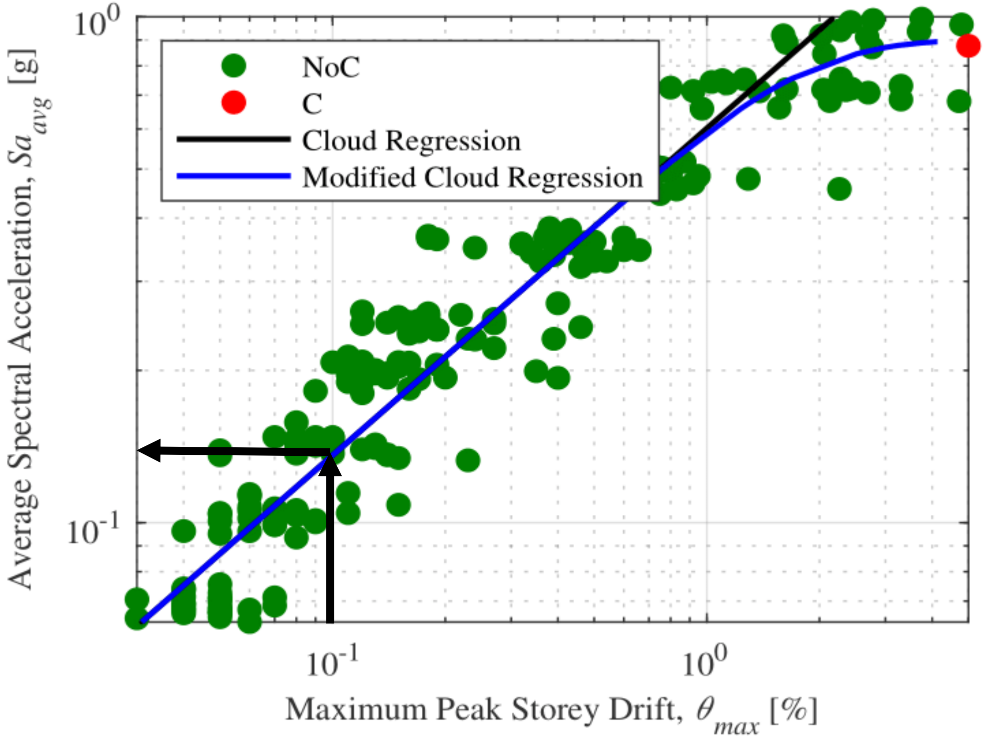


Cloud Analysis



Median Intensity Characterisation: Single Case

$\eta_{IM|\theta_{max}=0.1\%}$
$\approx 0.195g$

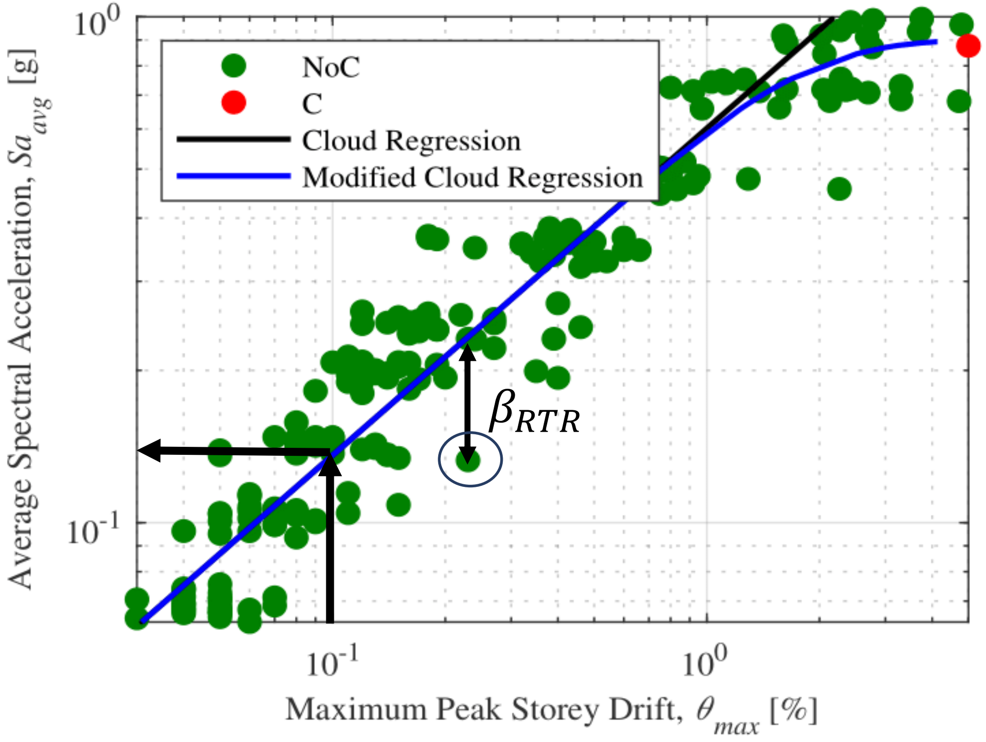


$$log\eta_{IM|EDP} = loga + b\ logEDP$$

Median intensity

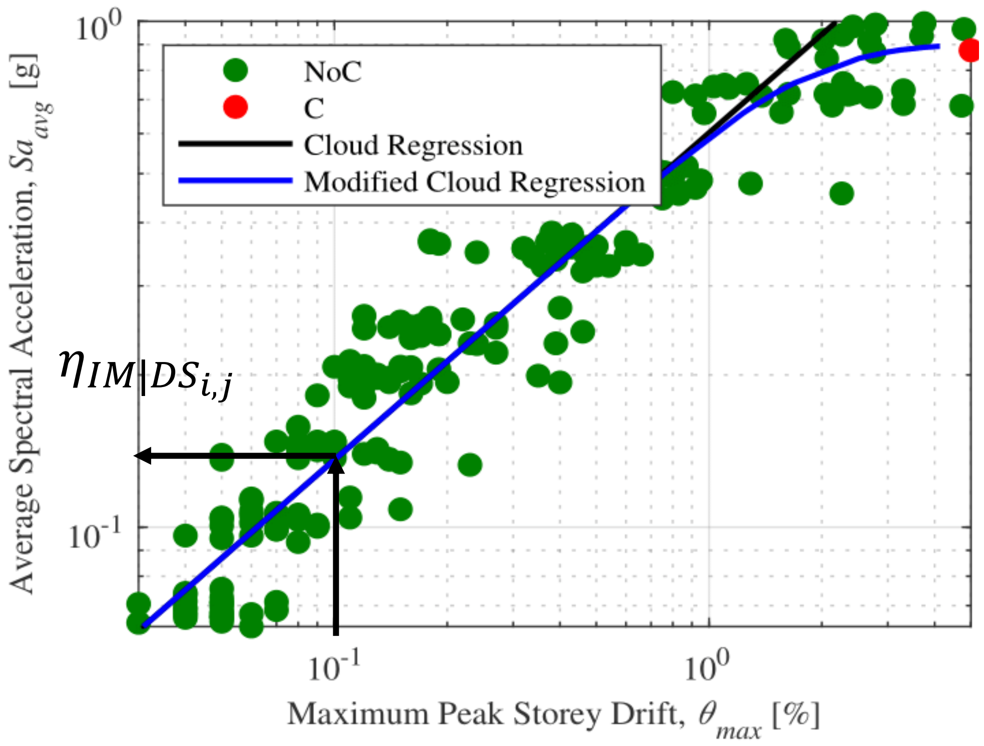
Engineering demand parameter

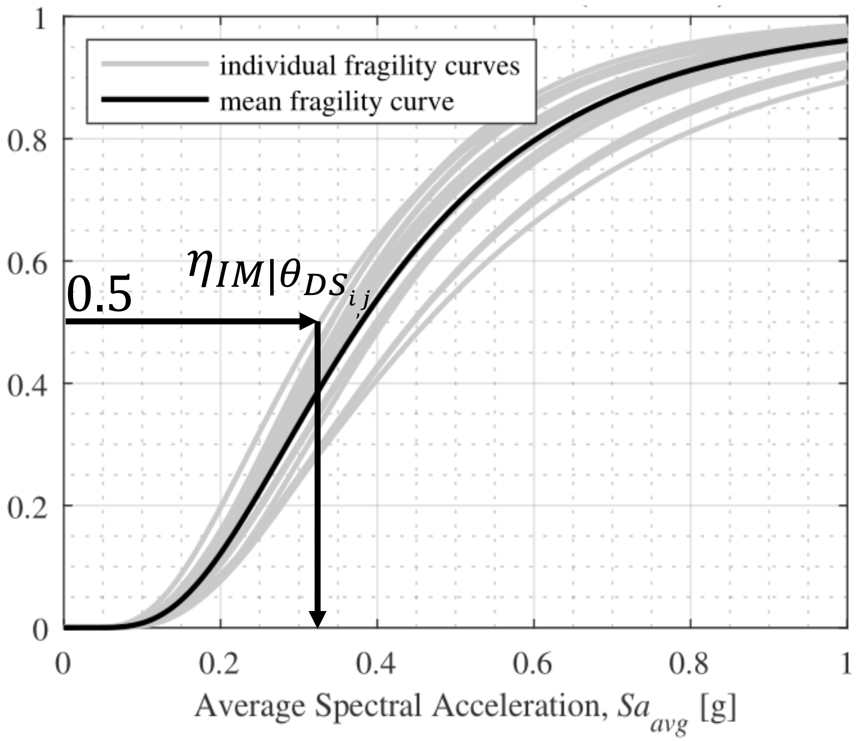
Epistemic Uncertainty: Single Case



$$\beta_{RTR} = \sigma_{logIM|EDP} = \sqrt{\frac{\sum_{i=1}^{n}(logY_i - log\eta_{IM|EDP})^2}{n-2}}$$

Median Intensity Characterisation: Assets



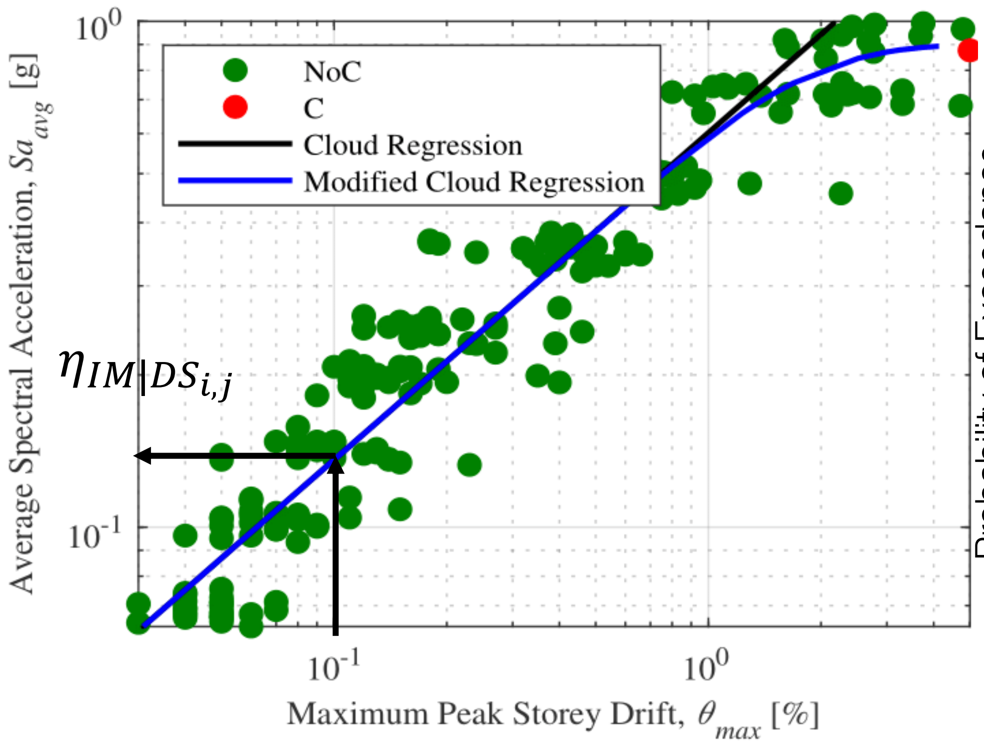


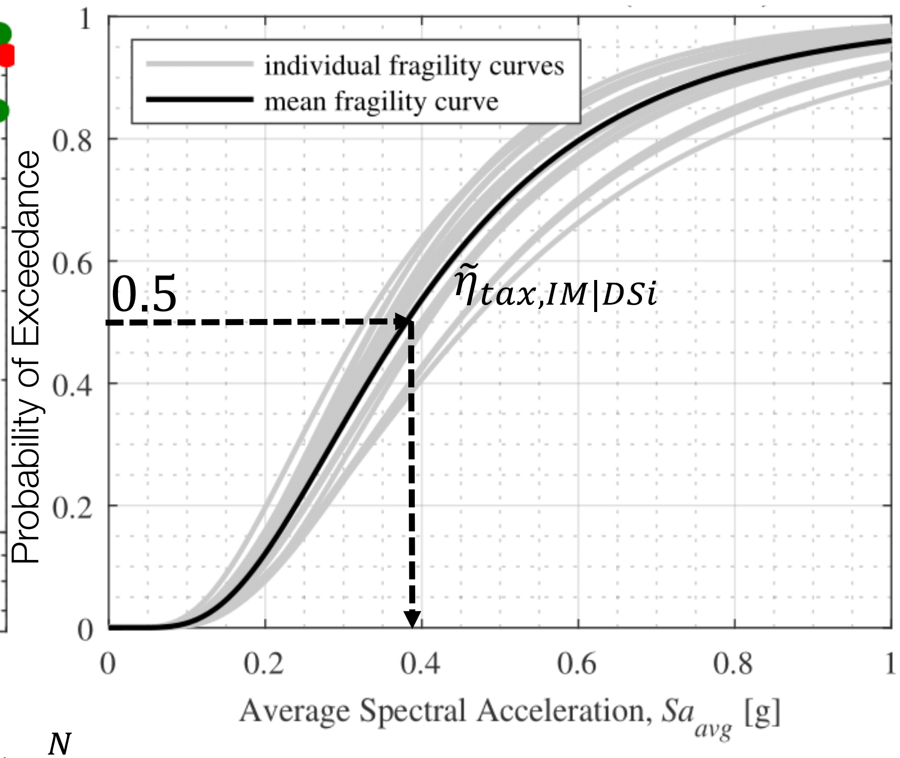
$$\underbrace{log\eta_{IM|DS_{i,j}}}_{} = loga + b\ \underbrace{logEDP_{DSi,j}}_{}$$

Median intensity for building j given DSi

Engineering demand parameter for the single-building j given DSi

Median Intensity Characterisation: Assets





$$\underbrace{\tilde{\eta}_{tax,IM|DSi}}_{\text{Taxonomy mean intensity}} = \frac{1}{N}\sum_{i}^{N} \underbrace{\eta_{IM|DSi}}_{\text{Single-building Median intensity given DS}}$$

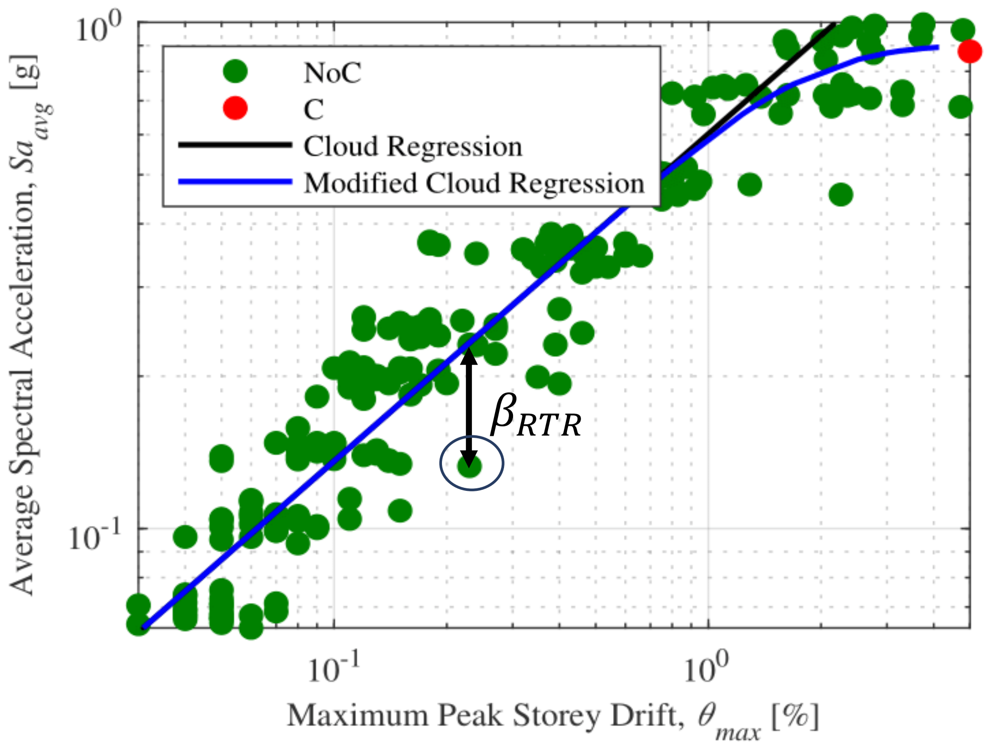
Treatment of Uncertainty: Assets

- The performance assessment of any structural typology requires due consideration of both aleatory and epistemic sources of uncertainty
- The aleatory uncertainty is associated with the randomness in ground motion records
- The epistemic uncertainty relates to uncertainties in the numerical modelling
- The law of total variance is used to estimate the total uncertainty associated with a taxonomy class

$$\underbrace{\beta_{lnY_{tax,total}}}_{\text{total dispersion associated with the taxonomy}} = \sqrt{\underbrace{\beta^2_{lnY_{intra}}}_{\text{Intra-building variability}} + \underbrace{\beta^2_{lnY_{inter}}}_{\text{Inter-building variability}} + \underbrace{\beta^2_{MDL}}_{\text{Modelling uncertainty}}}$$

Treatment of Uncertainty: Assets

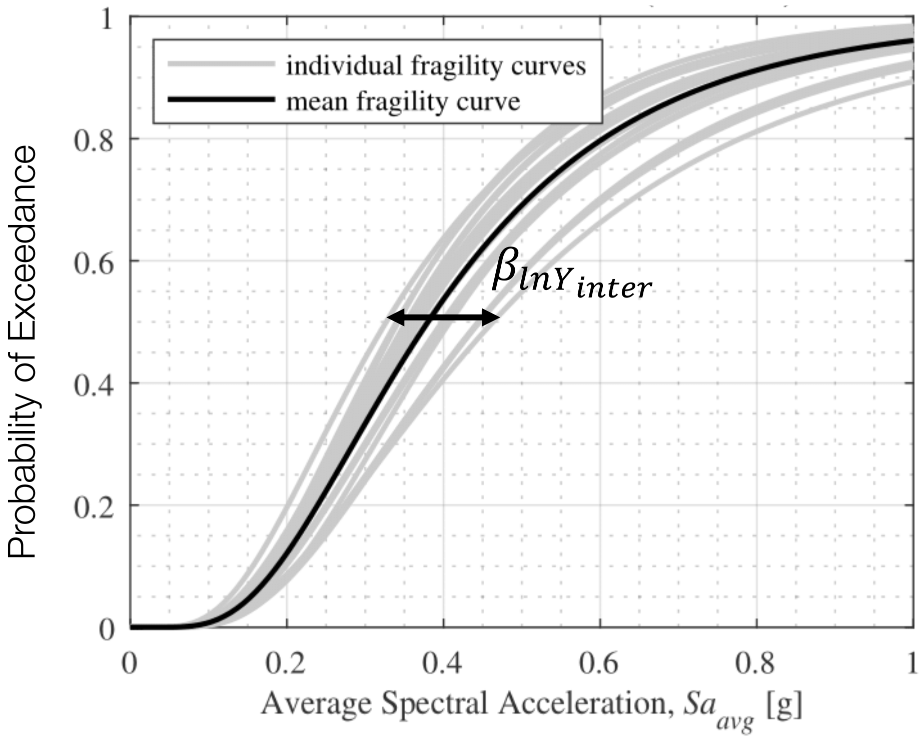
$$\beta_{lnY_{tax,total}} = \sqrt{\boxed{\beta^2_{lnY_{intra}}} + \beta^2_{lnY_{inter}} + \beta^2_{MDL}}$$



$$\beta^2_{lnY_{intra}} = \frac{1}{N}\sum_{i=1}^{N}\beta^2_{RTR,i}$$

Treatment of Uncertainty: Assets

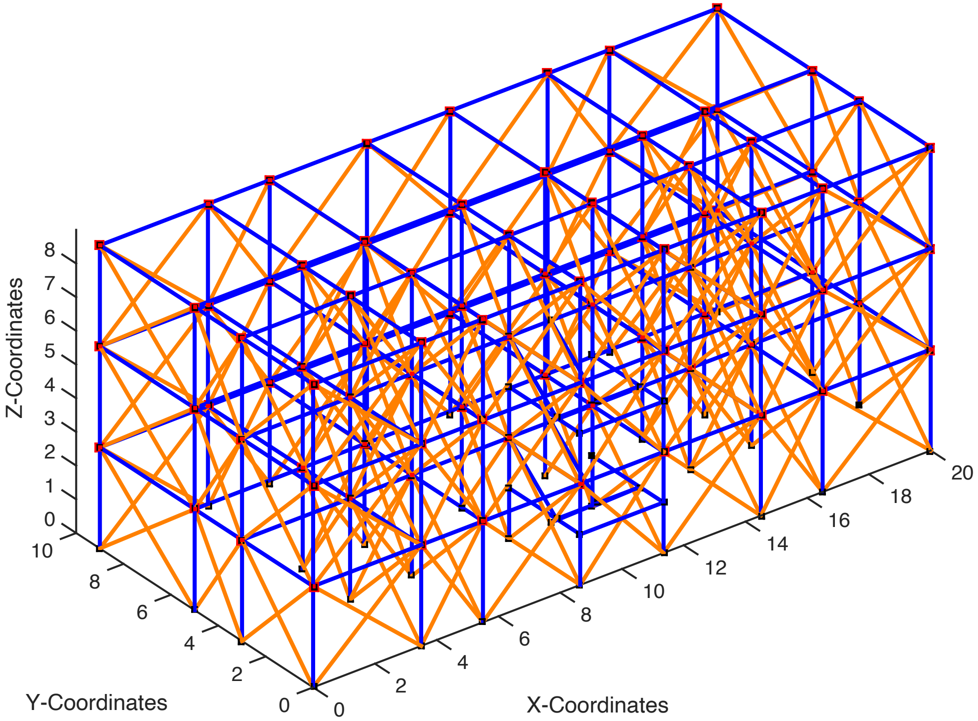
$$\beta_{lnY_{tax,total}} = \sqrt{\beta^2_{lnY_{intra}} + \boxed{\beta^2_{lnY_{inter}}} + \beta^2_{MDL}}$$



$$\beta_{lnY_{inter}} = \sqrt{\frac{\sum_{i=1}^{N}(log\eta_{IM|DSi,j} - log\tilde{\eta}_{IM|DSi})^2}{N}}$$

Treatment of Uncertainty: Assets

$$\beta_{lnY_{tax,total}} = \sqrt{\beta^2_{lnY_{intra}} + \beta^2_{lnY_{inter}} + \boxed{\beta^2_{MDL}}}$$



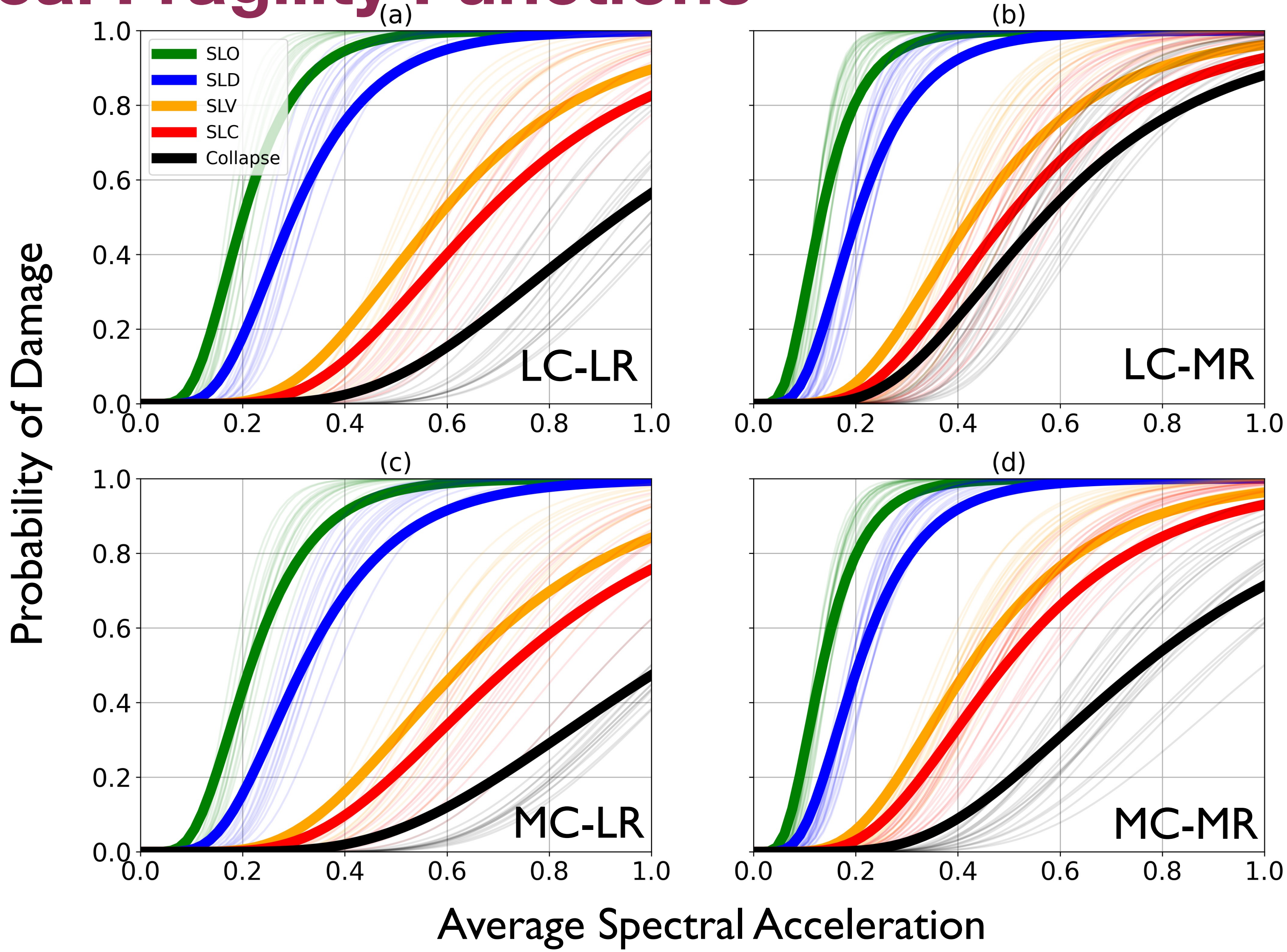
$$\beta_{MDL} = 0.34$$

According to O'Reilly and Sullivan

for two-to-six

storey infilled RC buildings

Analytical Fragility Functions



Empirical Fragility Functions

- Empirical fragility functions are the end result of convolving two layers of information in combination with robust statistical tools

➢Observed damage to buildings

➢Ground-motion fields (GMFs)

Observed Building Damage

- DaDO: Database of Observed Damage

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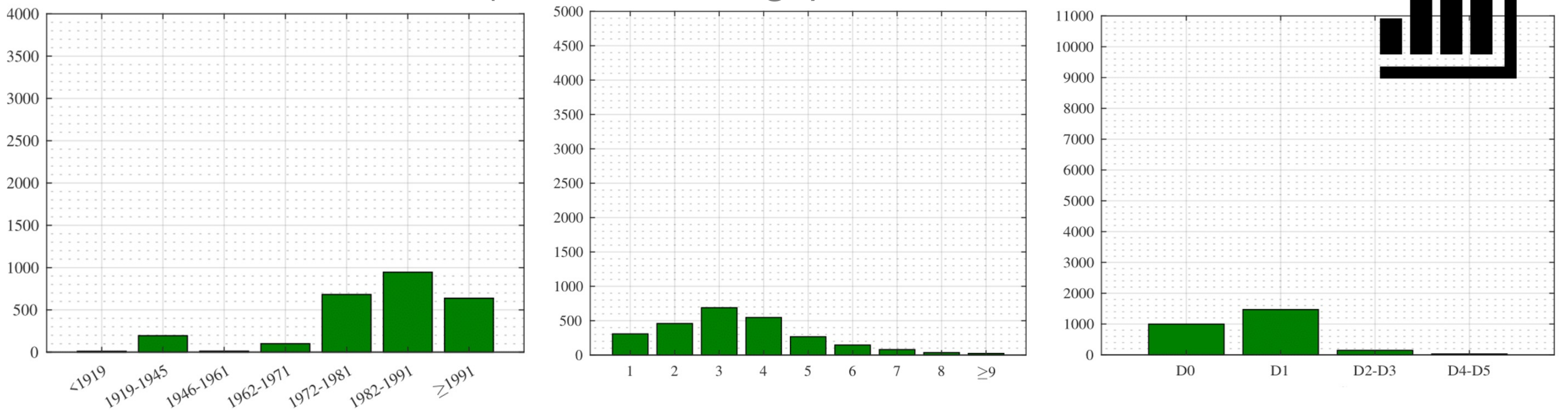
- Friuli 1976
- Irpinia 1980
- Abruzzo 1984
- Umbria-Marche 1997
- Pollino 1998
- Molise-Puglia 2002
- Emilia 2003
- L'Aquila 2009
- Emilia 2012
- Garfagnana-Lunigiana 2013
- Central Italy 2016 - 2017
- Mugello 2019

Observed Building Damage

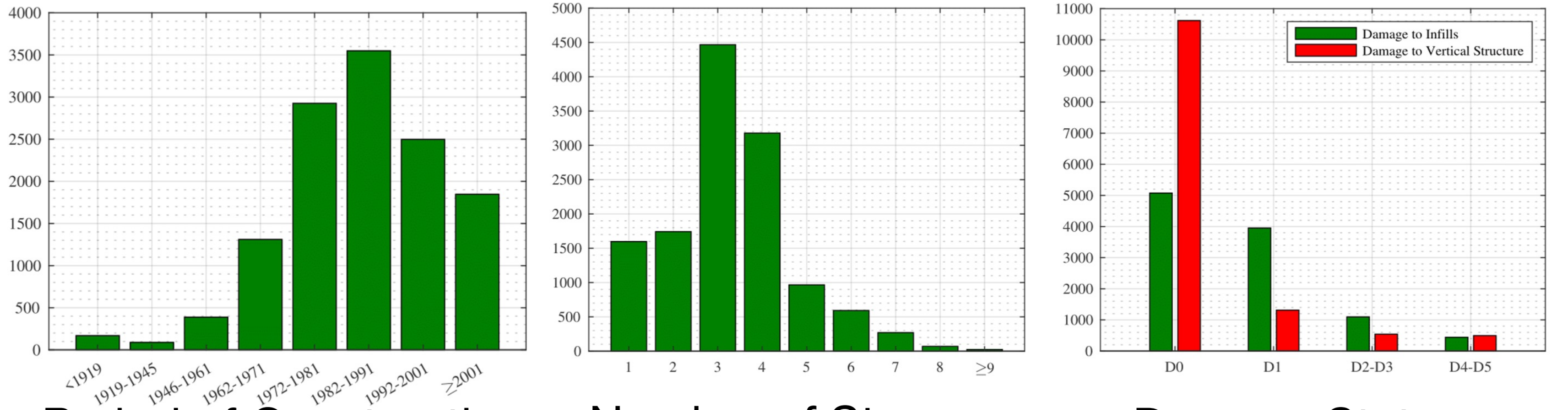
- Building characteristics and spatial distributions (DaDO)

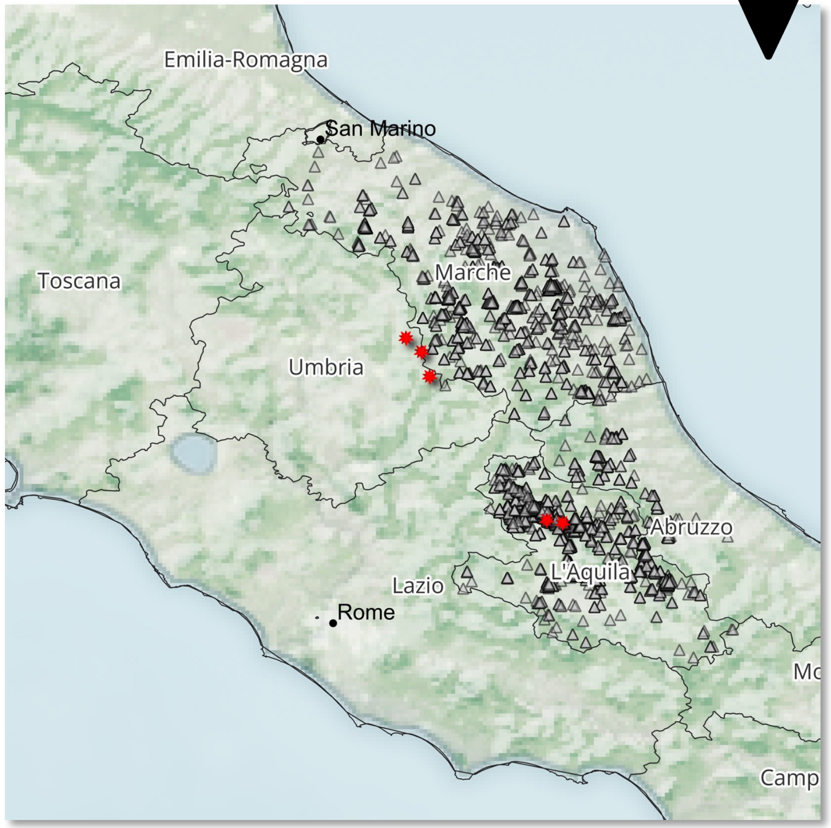
Umbria-Marche 1997 (2164 Buildings)



Building Count

L'Aquila 2009 (8502 Buildings)





Period of Construction | Number of Storeys | Damage States | Inspected Building Locations

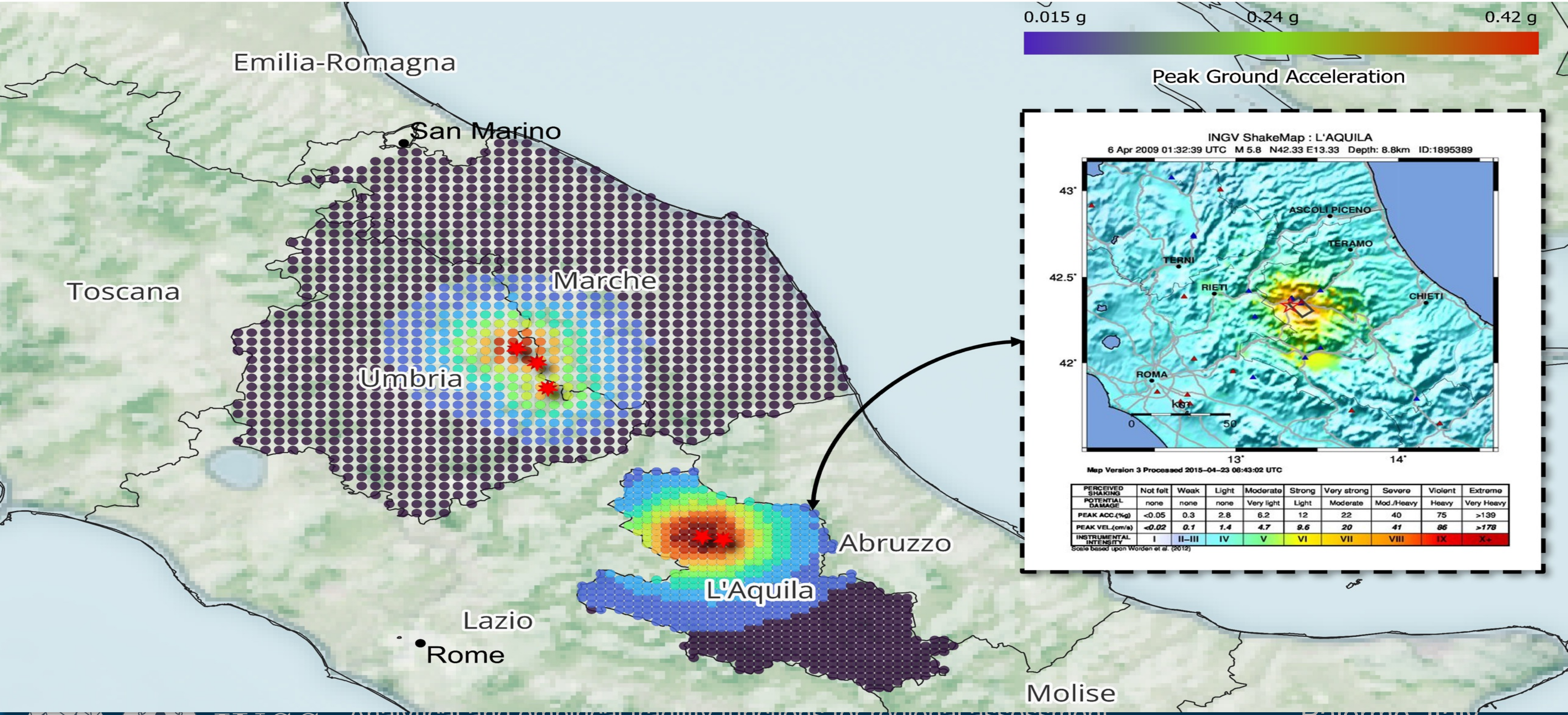
Ground-Motion Fields

- Physically realistic ground-motion fields are a combination of:
  - Handling of ground-motion models (GMMs) for the estimation of spectral intensities (Bindi *et al.* 2011) and indirect approach highlighted in Kohrangi *et al.* 2018 to estimate Sa_{avg} values and the total associated uncertainty
  - Conditioning of GMMs on seismic station data (ITACA) to account for "ground-truth" in the within-event uncertainty (Engler *et al.* 2022)
  - Spatial correlation to consider the spatial dependence in the joint probability distribution function of an intensity measure given a rupture scenario
  - Cross-correlation between IMs to consistently sample ground-shaking intensities from a GMM distribution over multiple IMTs and preserving the spectral shape properties

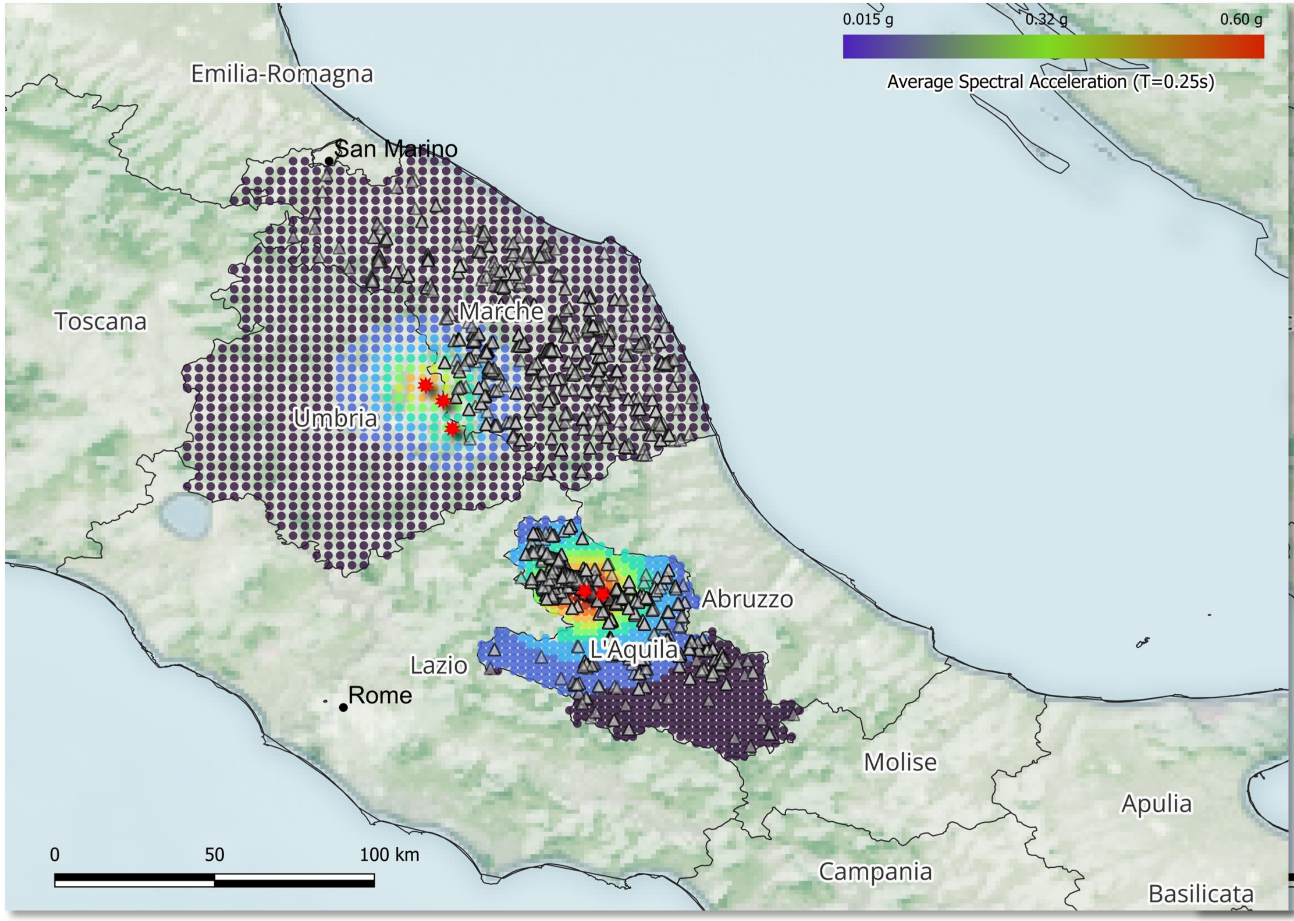
https://github.com/gem/oq-engine/tree/master/openquake/hazardlib/

- *Bindi, D., Pacor, F., Luzi, L. et al. Ground motion prediction equations derived from the Italian strong motion database. Bull Earthquake Eng 9, 1899–1920 (2011). https://doi.org/10.1007/s10518-011-9313-z*
- [illegible] *Eng 16, [illegible]. doi: https://doi.org/10.1785/0120210177*

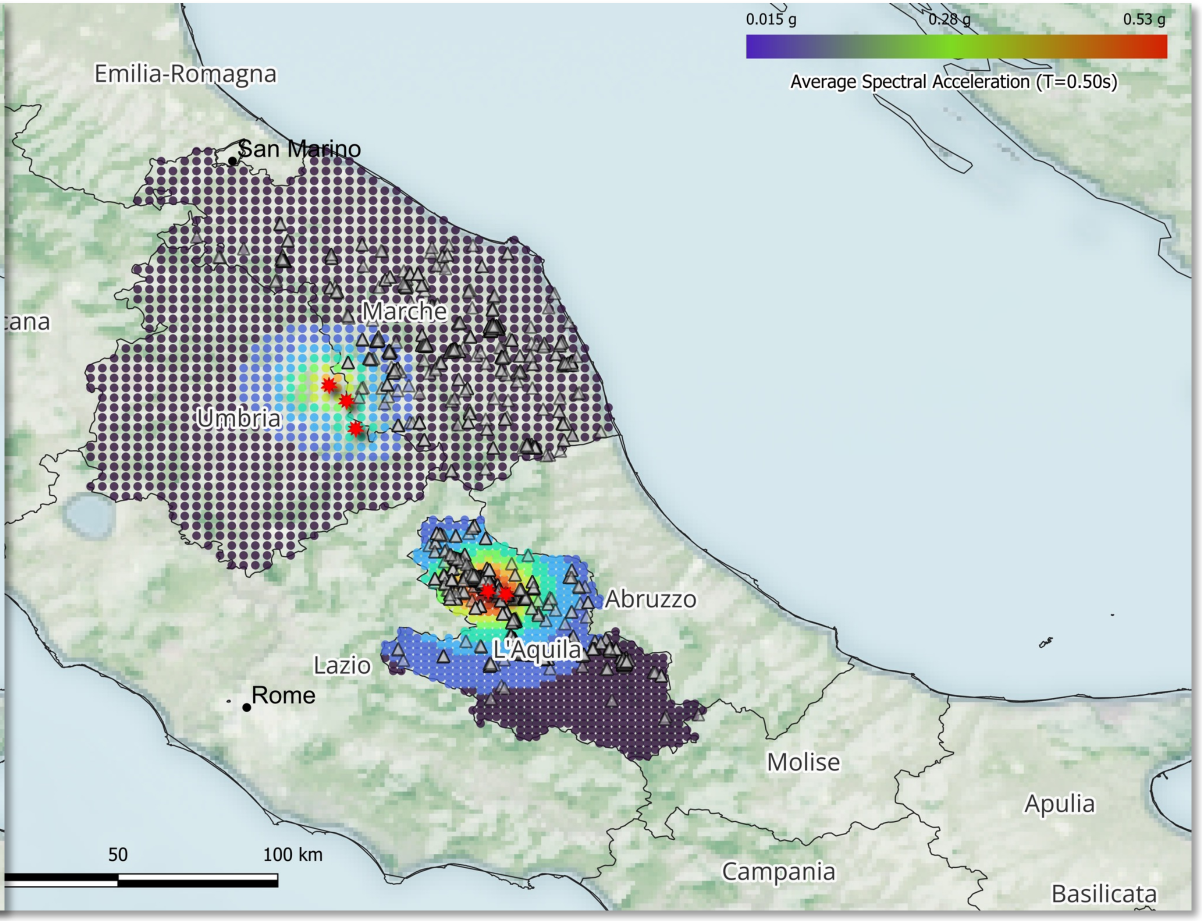
Ground-Motion Fields Validation



Sa_{avg}–based Ground-Motion Fields

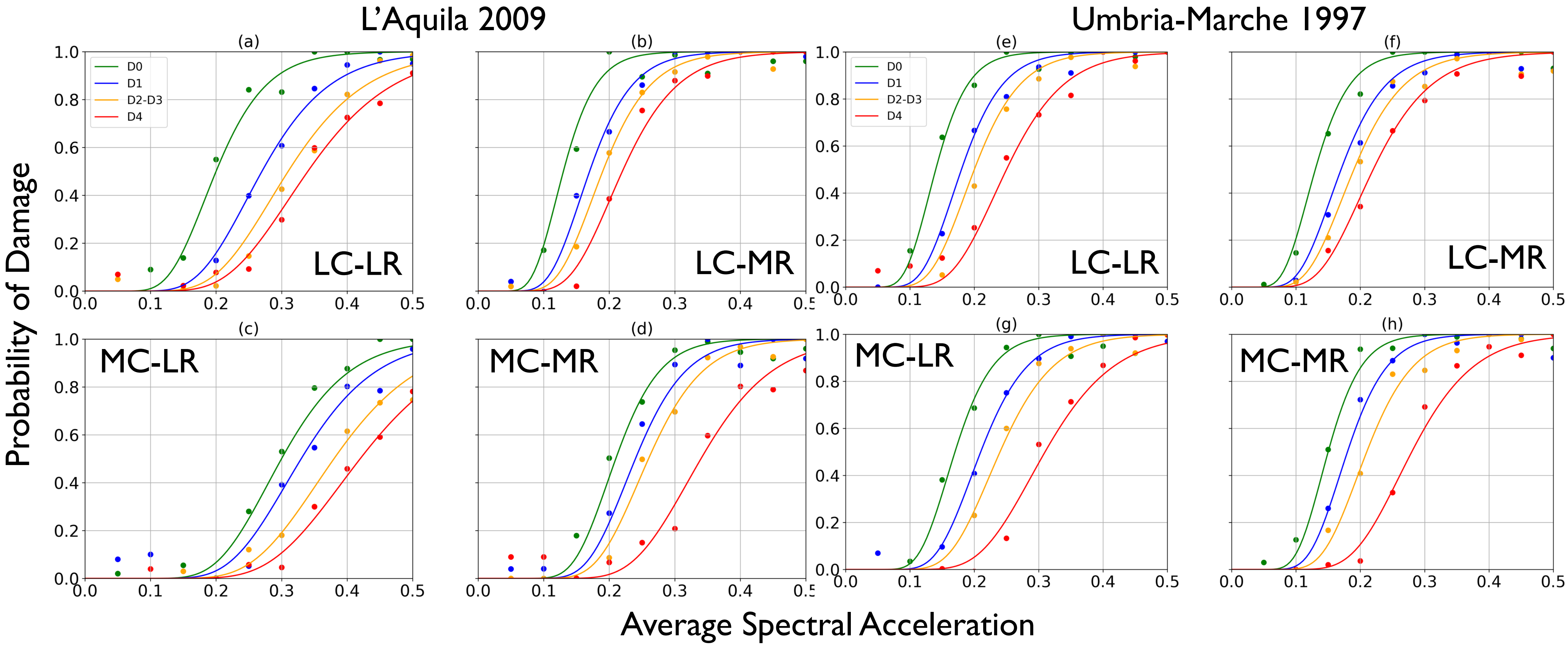


Sa_{avg} (0.25s)-based GMFs for Low-Rise Buildings



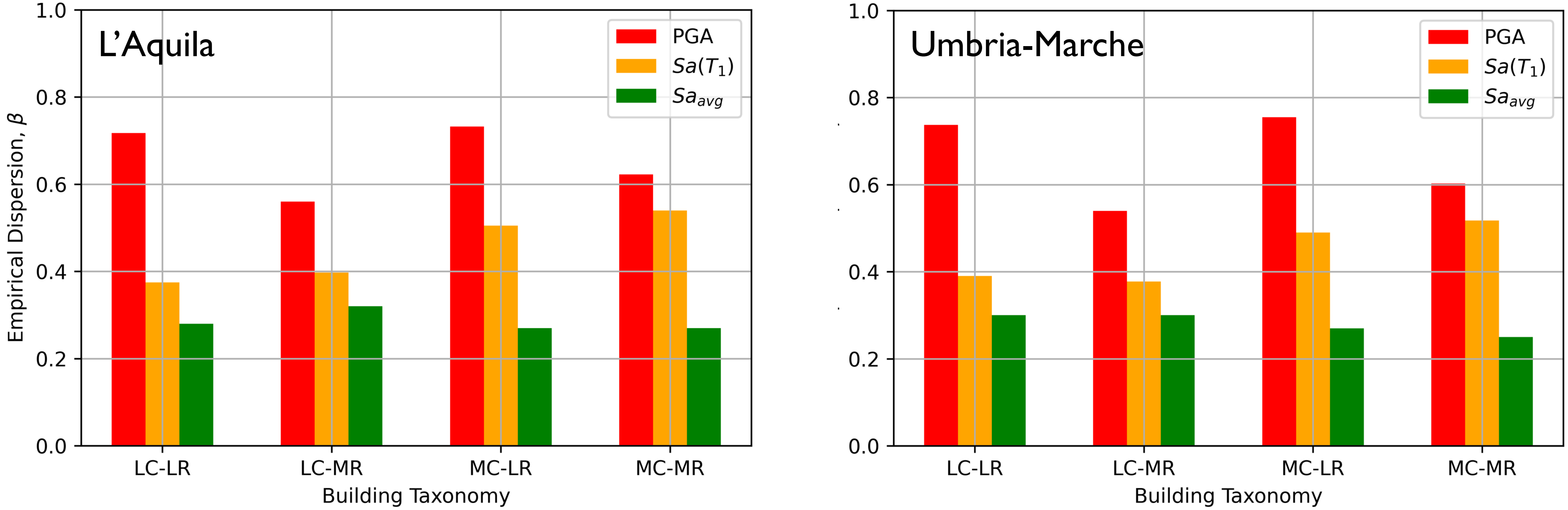
Sa_{avg} (0.50s)-based GMFs for Mid-Rise Buildings

Empirical Fragility Functions



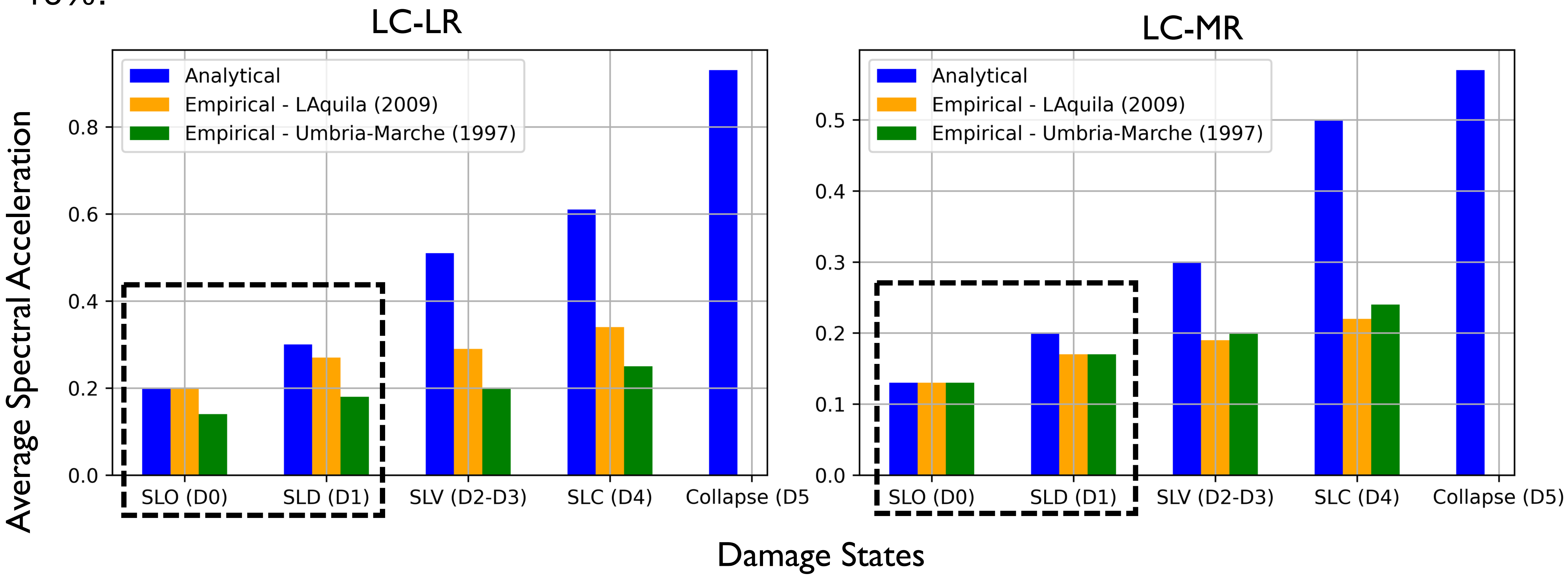
Discussion

- The dispersion values associated with the fitted empirical Sa_{avg}-based fragilities were compared to dispersions considering conventional IMs such as $Sa(T_1)$ and PGA



Discussion

- A good match between analytical and empirical FFs with regards to the serviceability DSs (i.e., operational and damage limitation) was observed, with reasonable errors varying between 0 and 16%.



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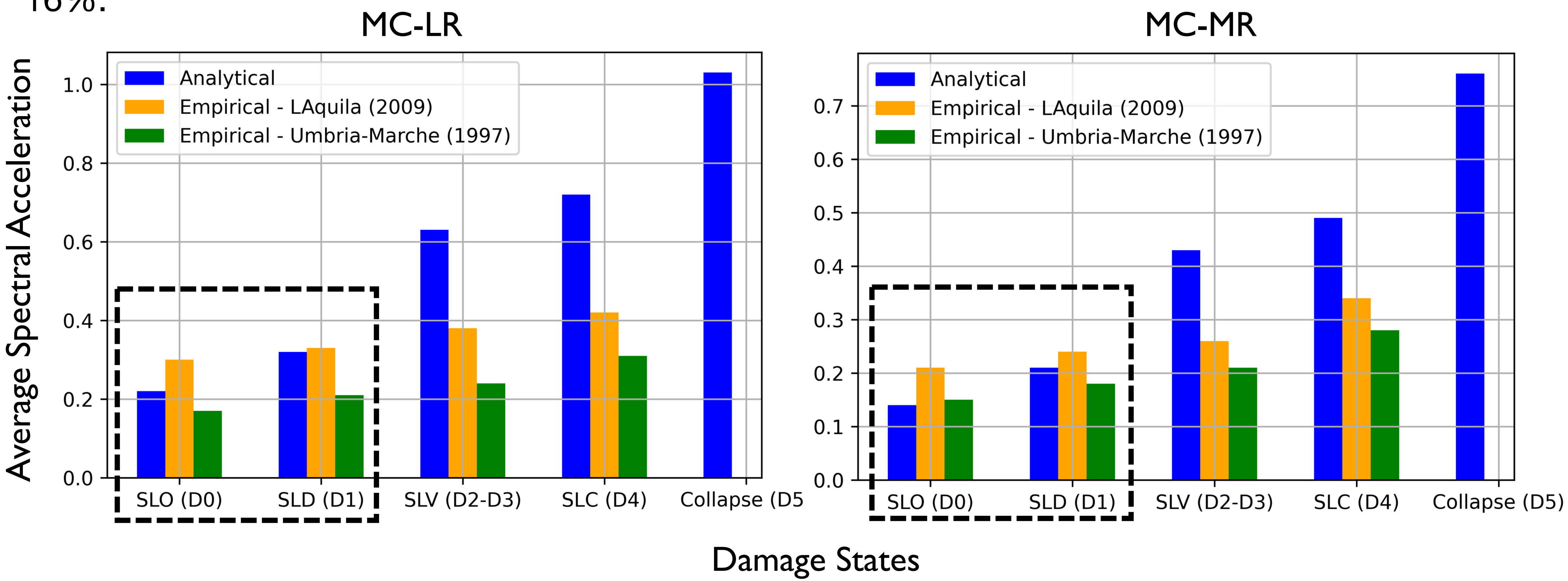
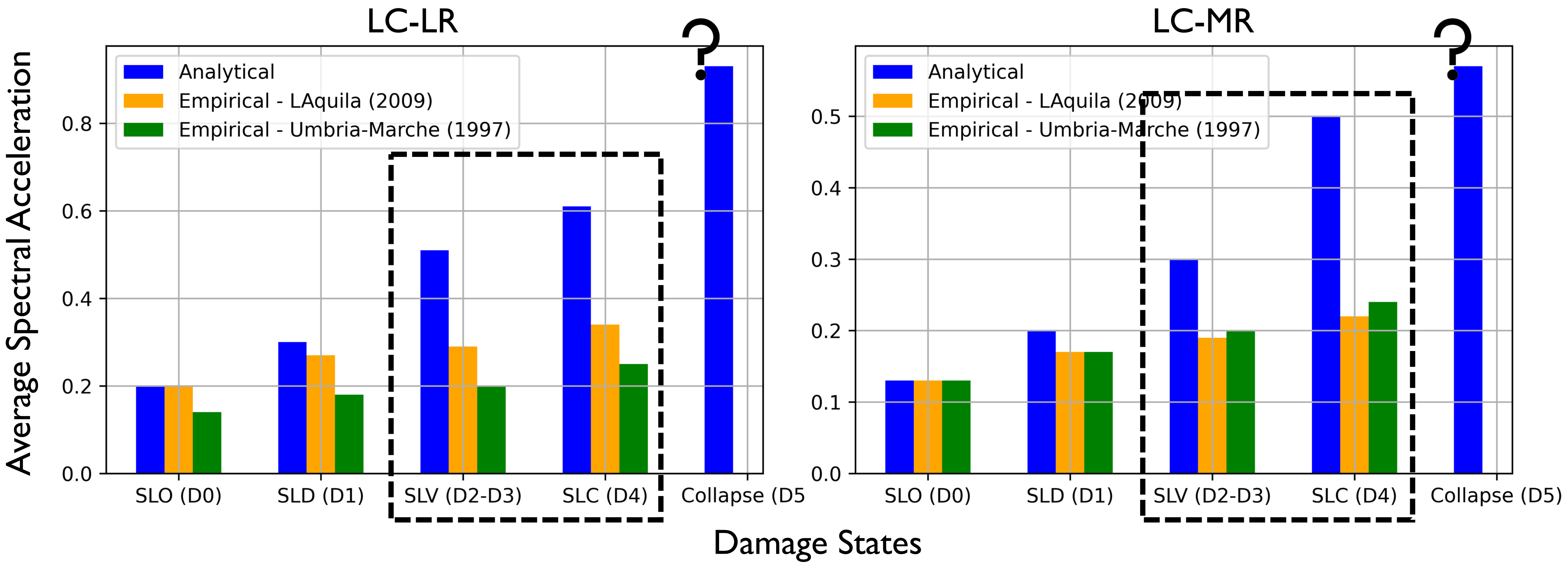


Discussion

- For the life-safety and near-collapse DSs, it can be seen that the analytical FFs tended to consistently overestimate the median intensities with respect to the empirical observations



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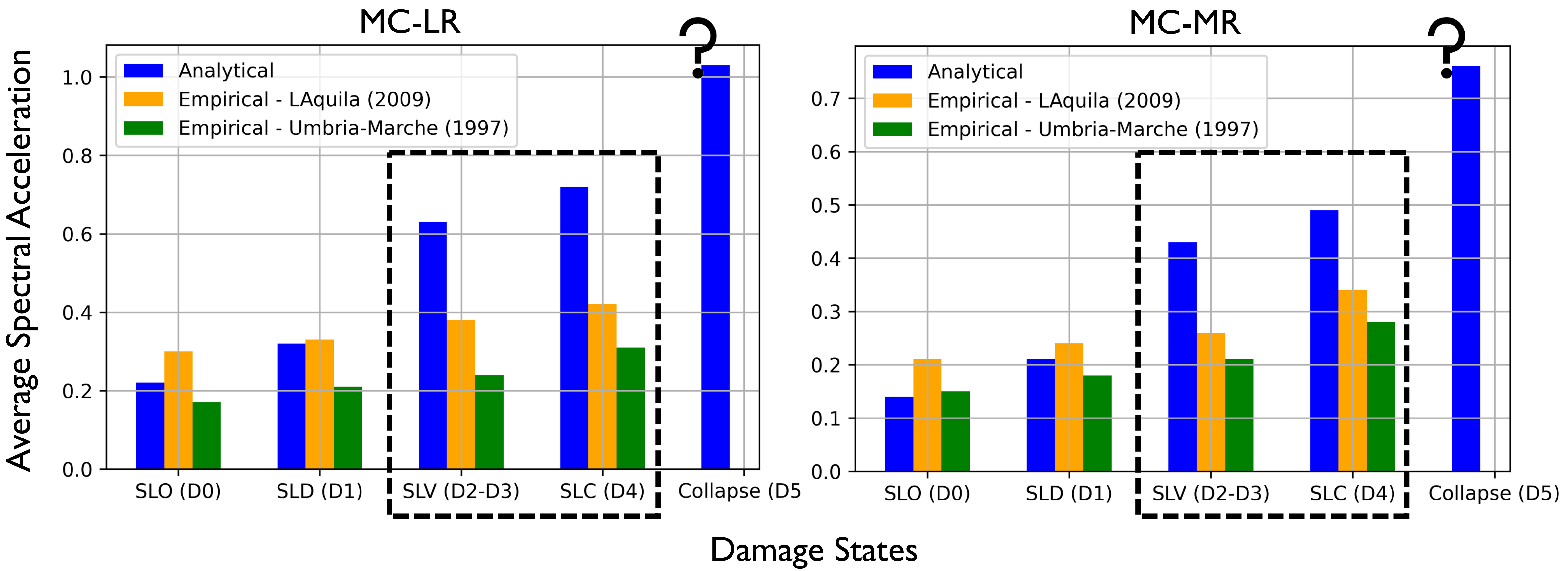

Discussion

- Quality of data particularly for the 1997 Umbria-Marche earthquake sequences, and the AeDES form before 2002:
  - ➢Inability to encompass all potential structural component types;
  - ➢Equal classification of the seismic behaviour among typologies that appeared similar aesthetically

- Damage accumulation in buildings following earthquake sequences
  - ➢Data was collected following the conclusion of EQ sequences
  - ➢Highlights the importance of input energy, hysteretic energy dissipation and proper ground motion record selection to characterise response to mainshock-aftershock sequences

- Uncertainty in the ground-shaking prediction and site conditions (e.g., Vs30)
- Harmonization in the DS definition between Italian code and macro-seismic scales
- Bias in data collection due to the differences in DS perception from one evaluator to another

Further information

- Find all material and papers on: https://gerardjoreilly.github.io/

- Presentation based on PhD thesis work of Dr. Al Mouayed Bellah Nafeh (currently at GEM Foundation)

- Recently published in Bulletin of Earthquake Engineering

Bulletin of Earthquake Engineering
https://doi.org/10.1007/s10518-024-01955-4

ORIGINAL ARTICLE

Check for updates

Fragility functions for non-ductile infilled reinforced concrete buildings using next-generation intensity measures based on analytical models and empirical data from past earthquakes

Al Mouayed Bellah Nafeh[1] · Gerard J. O'Reilly[1]

Received: 12 April 2024 / Accepted: 8 June 2024

Abstract
The regional seismic risk assessment of reinforced concrete (RC) building portfolios is a critical issue in earthquake engineering due to their high vulnerability and widespread distribution in seismic prone areas. A pertinent aspect in regional seismic risk applications is the ability to accurately quantify the exceedance of any damage state, generally via fragility functions. To this end, this study derives analytical fragility functions for large-scale seismic risk applications of non-ductile RC buildings with masonry infills characteristic of the Italian peninsula and Southern Europe in general. These were derived using a large database of archetype buildings developed to represent the temporal evolution in construction practice in Italy based on an extensive literature review and interviews with practising engineers and architects. Fragility functions for several infilled RC taxonomy classes were derived for multiple damage states using state-of-the-art analysis on detailed numerical models. Average spectral acceleration was adopted as the intensity measure throughout, since it has been shown to notably reduce dispersion and bias in quantifying the response

Questions?

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