Modelling Uncertainty in Existing Italian RC Frames

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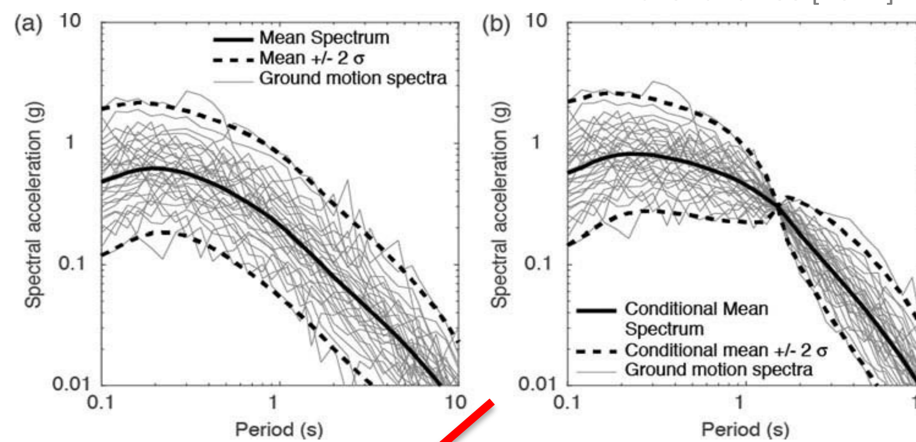
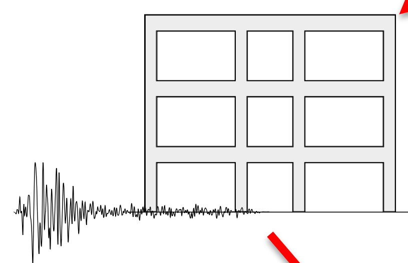
Background & Motivation

Baker and Lee [2017]

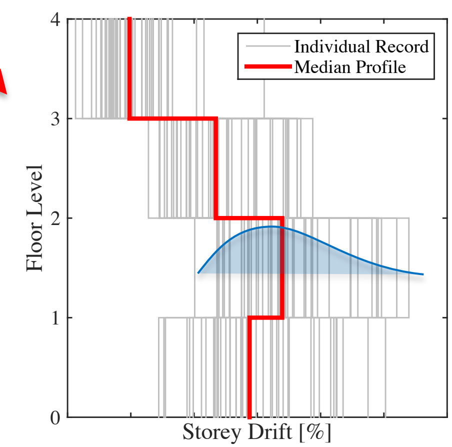


- We typically use a number of ground motions to characterise the response of a structure.
- In a more probabilistic setting for PBEE, the dispersion associated with a given demand parameter is of interest.
- Using many records can account for the "aleatory uncertainty" stemming from the natural randomness of ground motion records.
- The same argument exists for the numerical modelling, since we typically analyse a structure using a single numerical model, despite knowing that this model is not perfect: <u>**epistemic uncertainty.**</u>

NRHA of a single numerical model with a number of records



Distribution of response



Baker, Jack W., and Cynthia Lee. 2017. "An Improved Algorithm for Selecting Ground Motions to Match a Conditional Spectrum." *Journal of Earthquake Engineering*. doi:10.1080/13632469.2016.1264334.

Background & Motivation

- As highlighted on multiple occasions during a procedure to simply assess existing RC structures within a probabilistic setting, Fajfar & Dolšek [2012] note:

  "***For practical applications, predetermined default values for the dispersion measures, based on statistical studies of typical structural systems, are needed."***

  before concluding the manuscript with:

  "***Default values for dispersion measures are needed***".

- This paper aims to provide such default values of modelling uncertainty to be used when conducting a seismic assessment of gravity load design (GLD) RC frames with masonry infill in Italy.

Fajfar, P., and Dolšek, M. [2012] "A practice-oriented estimation of the failure probability of building structures," *Earthquake Engineering & Structural Dynamics*, Vol. 41, No.3, pp. 531–547.

Behaviour of Infilled GLD RC Frames

- Recent earthquakes in Italy have illustrated the vulnerability of existing gravity load designed (GLD) RC frames structures.

Beam-Column Joint

Masonry Infill Failure

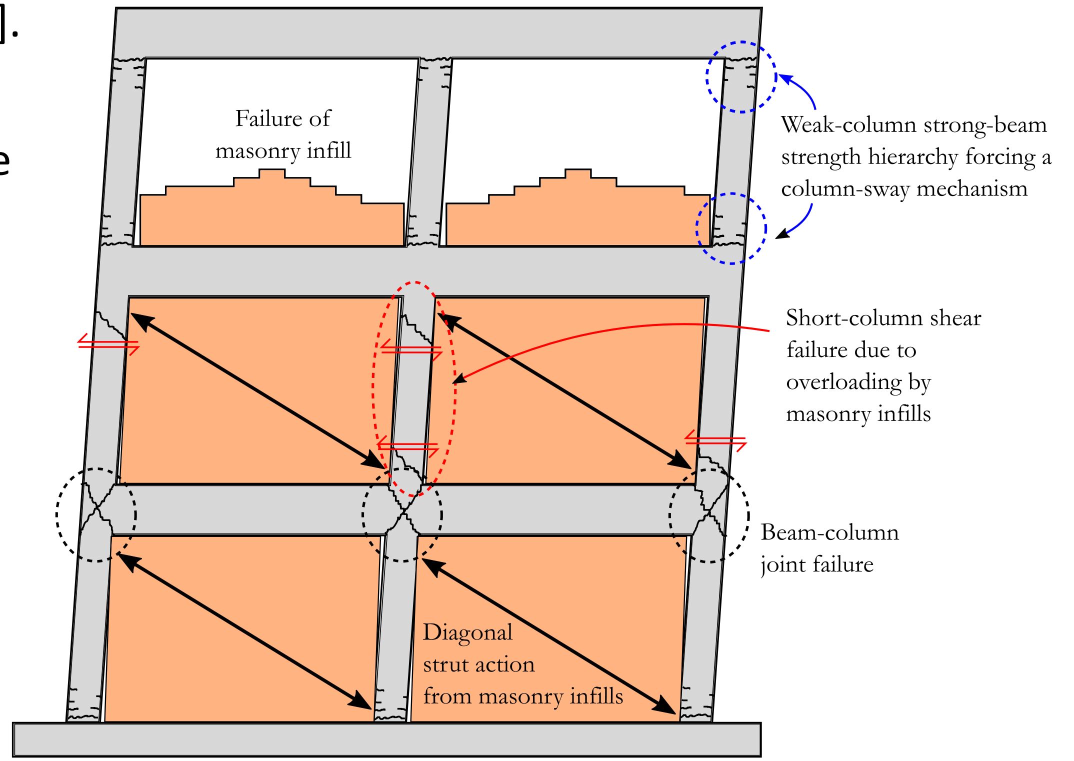
Soft Storey Collapse

Photos from reluis.it

Behaviour of Infilled GLD RC Frames

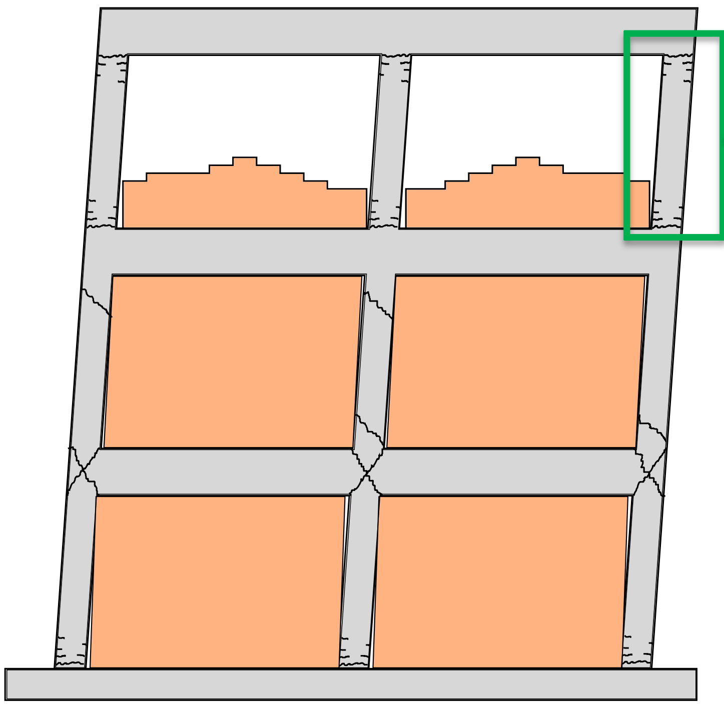
- Efficient numerical modelling approaches that capture the behaviour proposed by O'Reilly & Sullivan [2017].

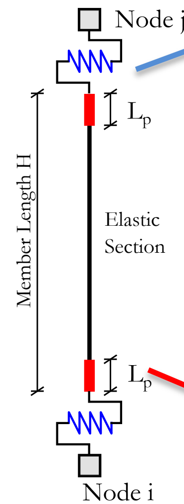
- Experimental testing and past damage observed following earthquakes have highlighted vulnerability elements:
  - Non-ductile columns with modified behaviour due to smooth bars.
  - Weak beam-column joints (no transverse shear reinforcement).
  - Shear failure of columns due to poor shear reinforcement and interaction with masonry infill.

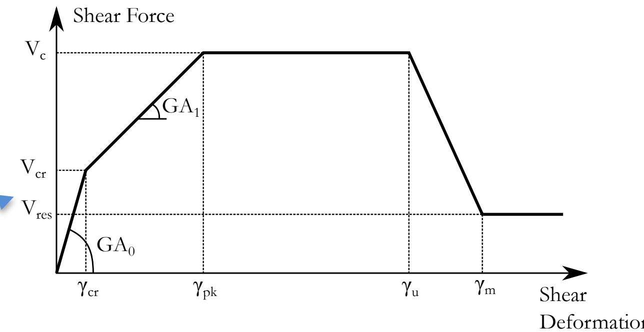


O'Reilly, G. J., and Sullivan, T. J. [2017] "Modelling Techniques for the Seismic Assessment of Existing Italian RC Frame Structures," *Journal of Earthquake Engineering*.

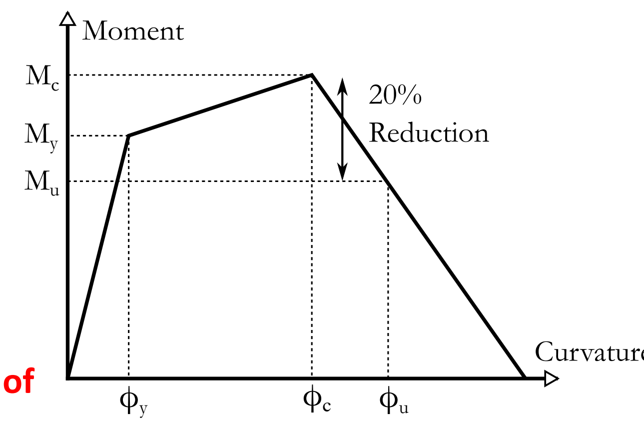
Beam-Column Element Modelling







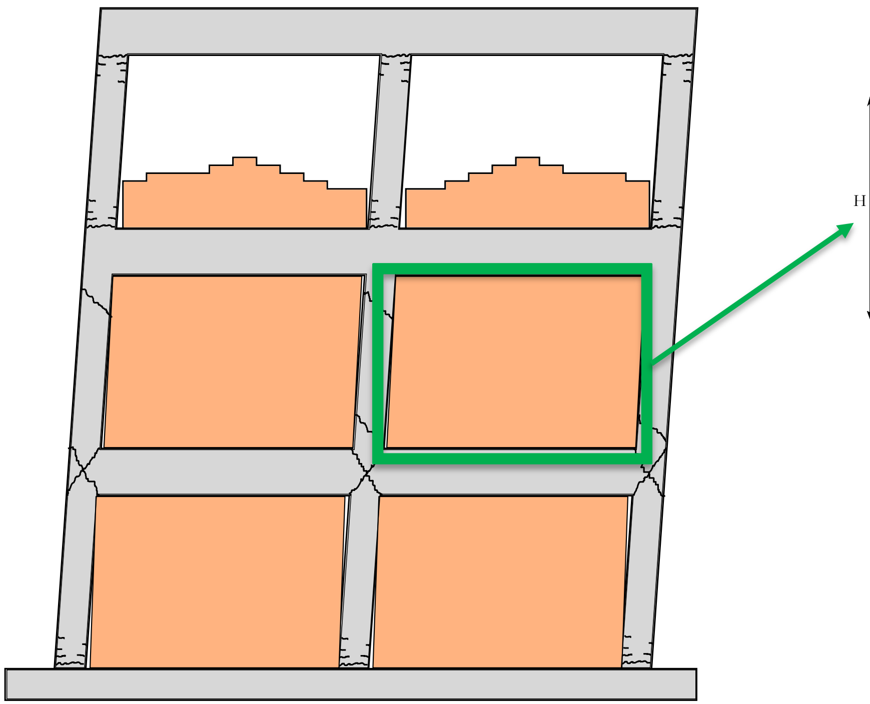
UCSD shear model adopted from previous calibration by Mergos & Kappos [2008, 2012] and Zimos et al. [2015].

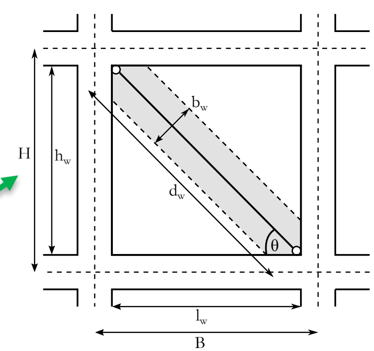


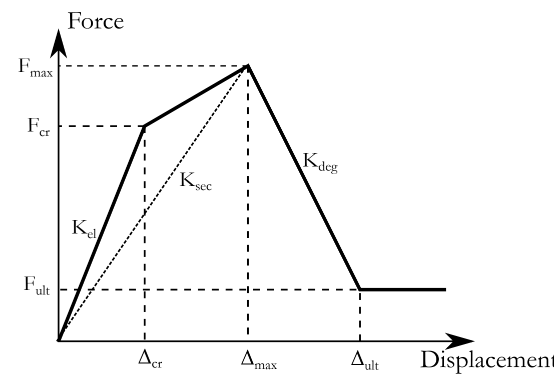
Lumped plasticity model adopted to capture ultimate ductility capacity and post peak strength degradation of members, which are calibrated to experimental data

O'Reilly, G. J., and Sullivan, T. J. [2017] "Modelling Techniques for the Seismic Assessment of Existing Italian RC Frame Structures," *Journal of Earthquake Engineering*.

Masonry Infill Modelling







Equivalent strut force deformation rule adopted from model proposed by Bertoldi et al. [1993] with more recent modifications by Sassun et al. [2015] to better match experimental test data.

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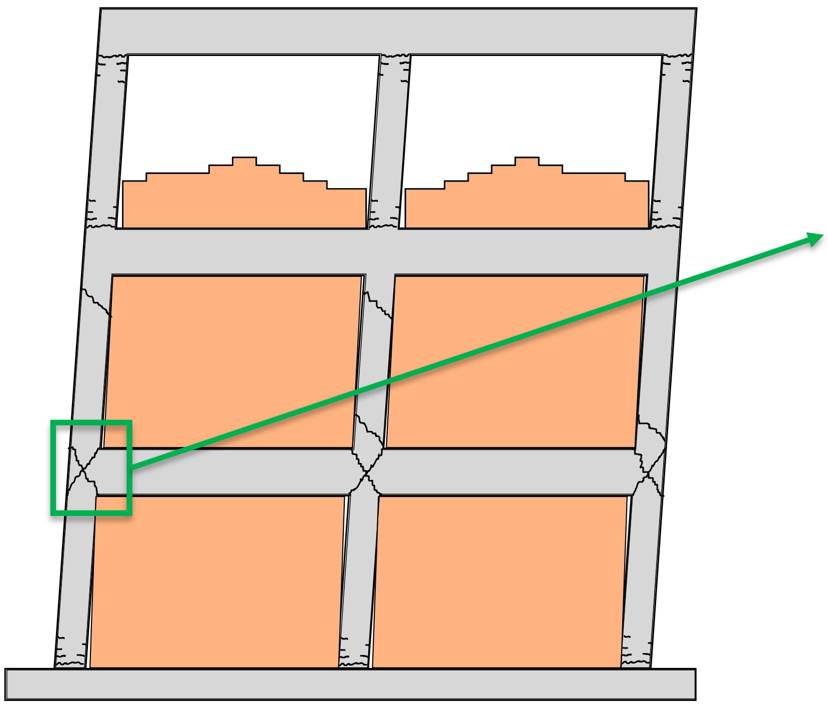
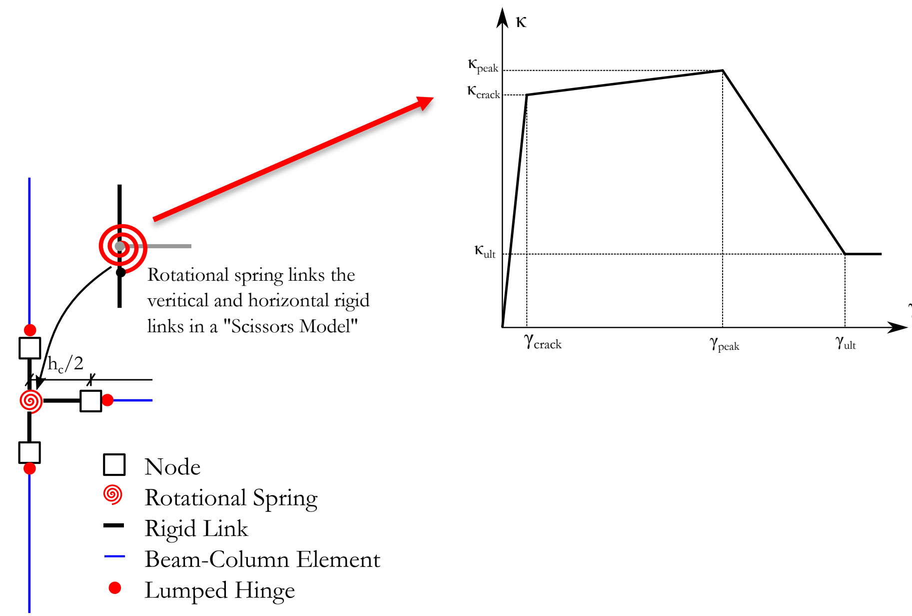
Beam-Column Joint Modelling



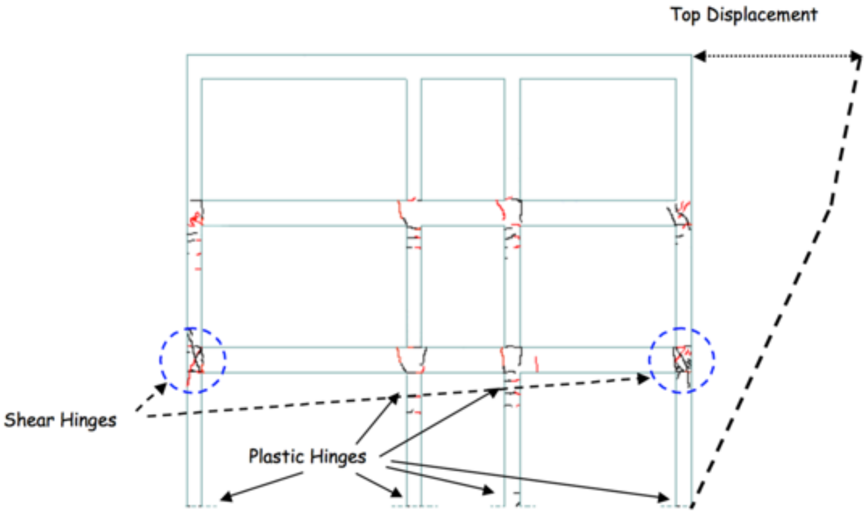


Scissors Model with rigid offsets in the joint centre are adopted to represent the vulnerable behaviour of the beam-column joints.

Calibrated to experimental data to capture joint strength and potential degradation.

O'Reilly, G. J., and Sullivan, T. J. [2017] "Modelling Techniques for the Seismic Assessment of Existing Italian RC Frame Structures," *Journal of Earthquake Engineering*.

Validation of Numerical Modelling

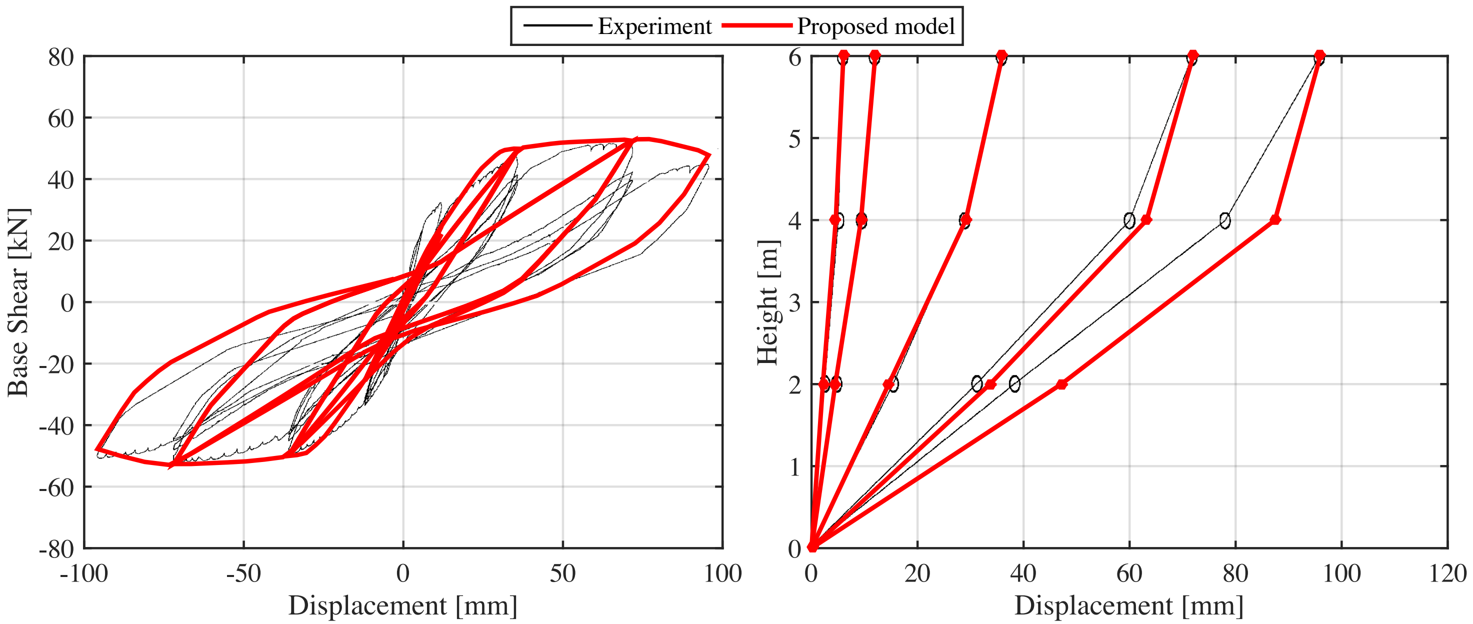


Observed Damage

- Three storey test frame designed to be representative of Italian RC frames constructed prior to 1970 and tested by Calvi et al. [2002] at the University of Pavia.
- Damage to the columns and exterior joints led to the formation of a non-ductile mechanism.
- The shear deformation of the joints led to a spread in drift over the two adjacent floors rather than a concentration in a single storey.

O'Reilly, G. J., and Sullivan, T. J. [2017] "Modelling Techniques for the Seismic Assessment of Existing Italian RC Frame Structures," *Journal of Earthquake Engineering*.

Validation of Numerical Modelling

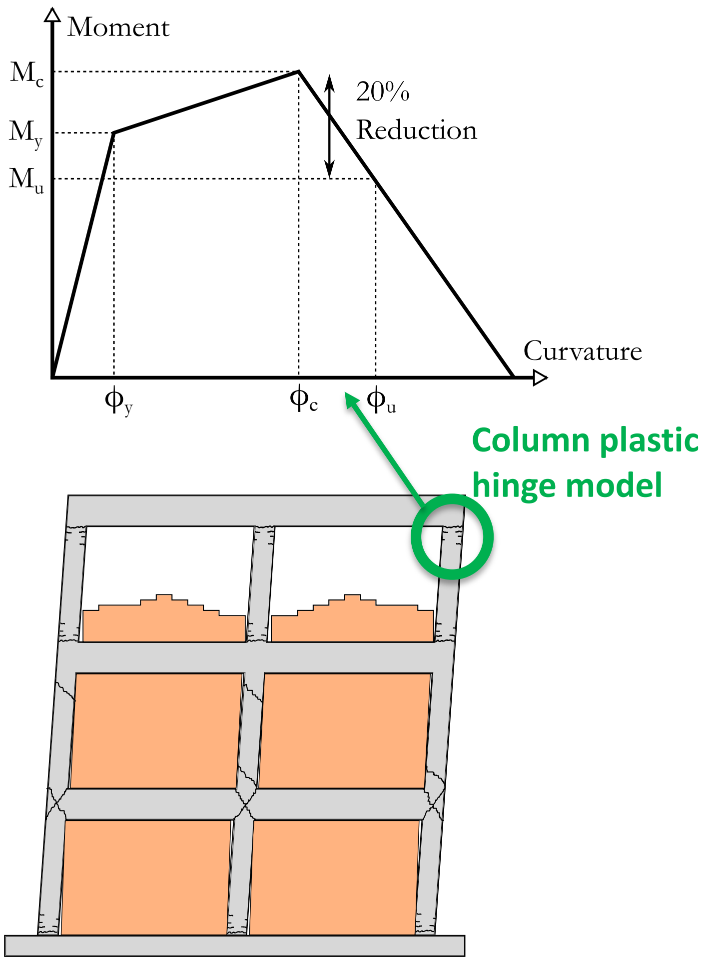


- Proposed modelling captures the behaviour well with the overall strength, stiffness and cycle transitions well represented.
- The displaced shape with each cycle peak is matched well here the joint failure on the ground floor along with the column damage on the first floor both captured.
- This highlights the models ability to adequately capture the different behavioural aspects particular to GLD RC frames in Italy.

O'Reilly, G. J., and Sullivan, T. J. [2017] "Modelling Techniques for the Seismic Assessment of Existing Italian RC Frame Structures," *Journal of Earthquake Engineering*.

Quantification of Modelling Uncertainty

- Using the statistical information from different components calibrated for GLD RC frames, a modelling uncertainty study can be conducted.
- The effects of modelling uncertainty are to be quantified for:
  - Collapse fragility function
  - Demand parameters (Drift & PFA)
- Allow for engineers to adopt empirical values of additional dispersion to account for modelling uncertainty in GLD RC frames with masonry infill.



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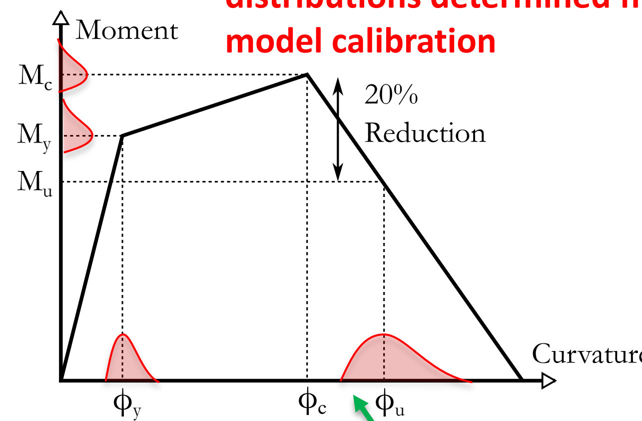
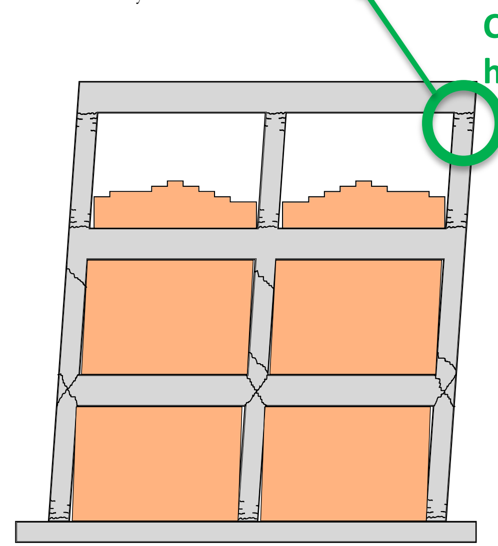
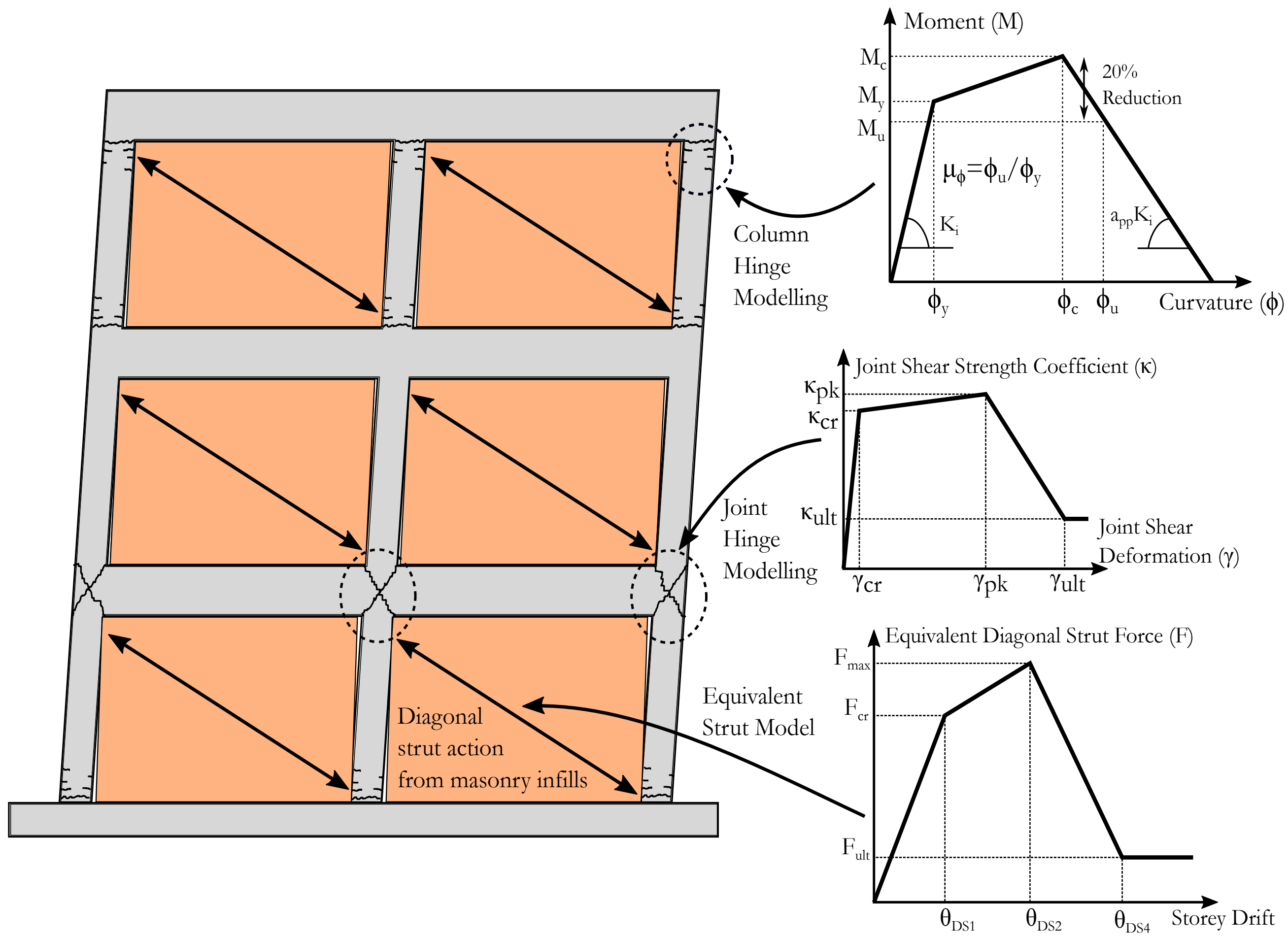
Treat the backbone parameters as random variables with distributions determined from model calibration



Column plastic hinge model



Random Variables

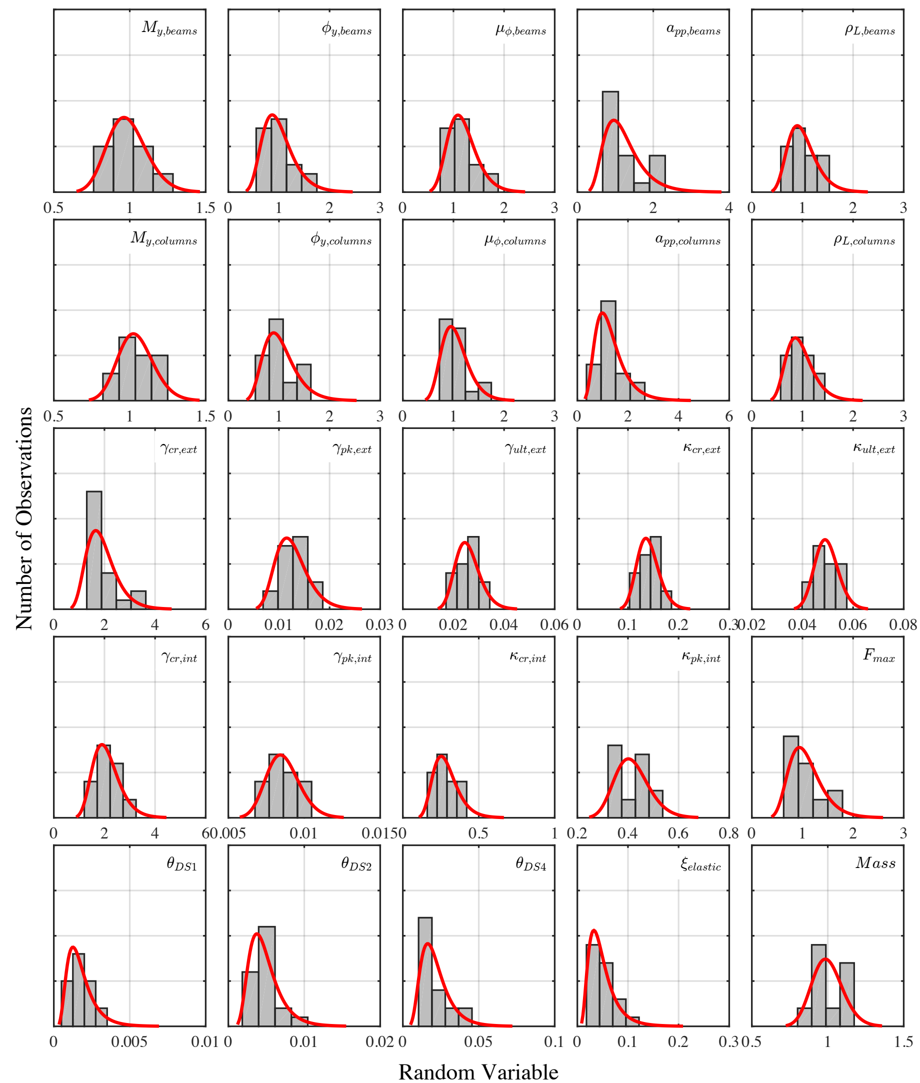


Random Variables

	#	RV	Description	Source	Median	Dispersion	Reference
Beams	1	M_y	Yield moment	Computed	-	0.122	O'Reilly and Sullivan [2017]
	2	ϕ_y	Yield curvature			0.287	
	3	μ_ϕ	Ultimate curvature ductility			0.326	
	4	a_{pp}	Post-peak stiffness ratio			0.413	
	5	ρ_L	Longitudinal reinforcement ratio			0.250	
Columns	6	M_y	Yield moment	Computed	-	0.122	O'Reilly and Sullivan [2017]
	7	ϕ_y	Yield curvature			0.287	
	8	μ_ϕ	Ultimate curvature ductility			0.326	
	9	a_{pp}	Post-peak stiffness ratio			0.413	
	10	ρ_L	Longitudinal reinforcement ratio			0.250	
Exterior Joints	11	γ_{cr}	Joint shear deformation at cracking	Test Data	0.0002	0.300	Estimate
	12	γ_{pk}	Joint shear deformation at peak capacity		0.0127	0.286	O'Reilly and Sullivan [2017]
	13	γ_{ult}	Joint shear deformation at ultimate capacity		0.0261	0.229	
	14	κ_{cr}	Joint shear strength coefficient at cracking		0.135	0.166	
	15	κ_{ult}	Joint shear strength coefficient at ultimate capacity		0.05	0.091	
Interior Joints	16	γ_{cr}	Joint shear deformation at cracking	Test Data	0.0002	0.300	Estimate
	17	γ_{pk}	Joint shear deformation at peak capacity		0.0085	0.133	O'Reilly and Sullivan [2017]
	18	κ_{cr}	Joint shear strength coefficient at cracking		0.29	0.237	
	19	κ_{pk}	Joint shear strength coefficient at peak capacity		0.42	0.163	
Masonry Infills	20	F_{max}	Infill diagonal strut capacity	Sassun et al. [2015]	-	0.300	Estimate
	21	θ_{DS1}	Storey drift at DS1 defined in Sassun et al. [2015]	Test Data	0.18%	0.520	Sassun et al. [2015]
	22	θ_{DS2}	Storey drift at DS2 defined in Sassun et al. [2015]		0.46%	0.540	
	23	θ_{DS4}	Storey drift at DS4 defined in Sassun et al. [2015]		1.88%	0.380	
Global	24	ξ	Elastic damping ratio	Assumed Value	0.05	0.600	Haselton et al. [2007]
	25	M	Floor mass	Given	-	0.100	

Model Realisations

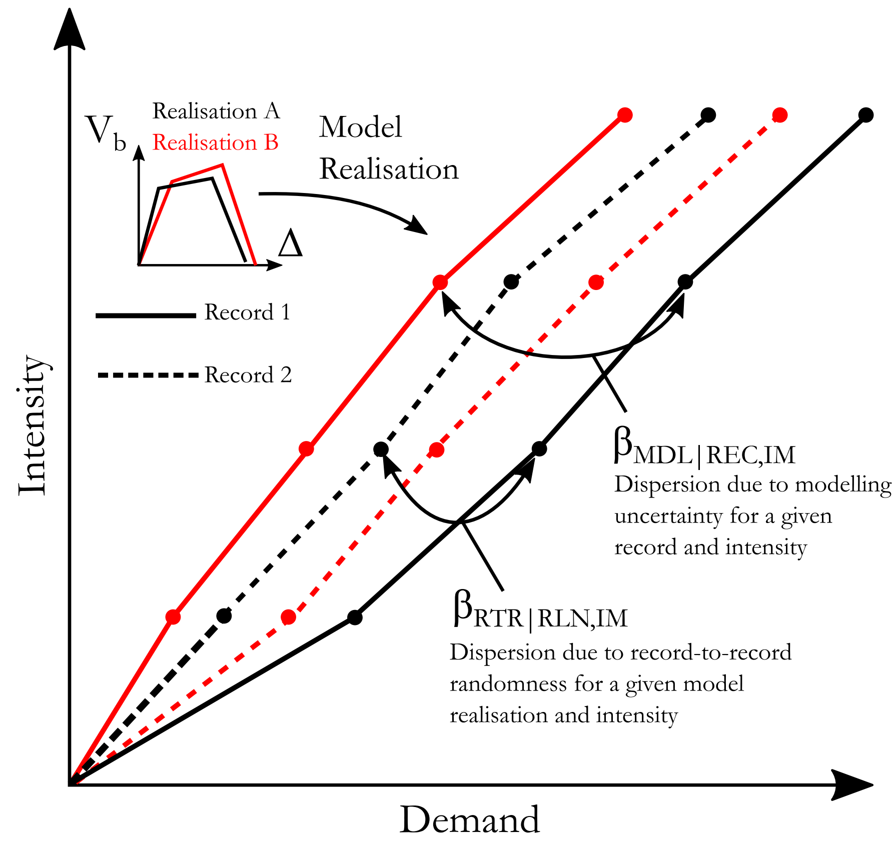
- A total of 25 random variables (RVs) identified.
- Using these RVs, 40 model realisations were sampled using a Correlation-Reduced Latin Hypercube Sampling method such as to avoid spurious correlations arising between different RVs.
- Care was taken to ensure that the sampled RVs of each model realisation actual made physical sense (e.g. M_y<M_c)
- These were analysed using 10 ground motion records from the FEMA P695 far field record set.
- Incremental Dynamic Analysis (IDA) was performed so as to characterise the evolution of the dispersion with respect to increasing intensity.



Methodology

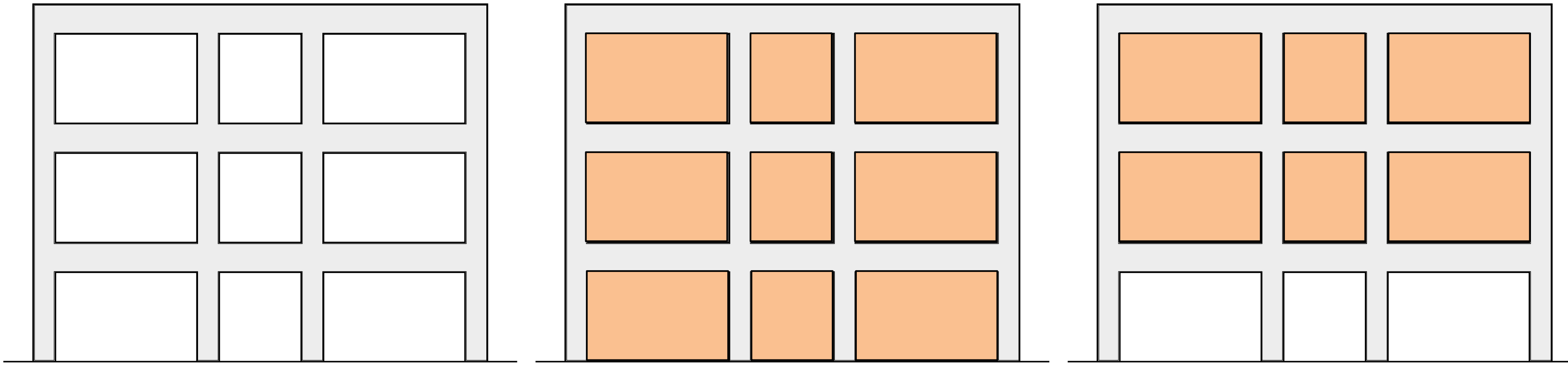
- For a given realisation, the record-to-record variability can be computed as the dispersion between records.

- Likewise, for a given ground motion record, the modelling uncertainty can be computed from the dispersion between model realisations.



Case Study Buildings

- 24 modelling variations are considered to consider the effects of masonry infill on the response.



MODELLED WITHOUT INFILL | **FULLY INFILLED** | **PILOTIS INFILL**

Two types of masonry: Strong (30cm hollow brick)
Weak (8cm hollow brick)

Both single and double strut masonry infill models to examine the impact of potential shear failure in the columns

Analysis Results

- Incorporating the modelling uncertainty is typically done by inflating the dispersion due to record-to-record variability using as SRSS combination.
- As this study focuses on both the collapse fragility and the demands in the building, we will refer to the following:

COLLAPSE

$$\beta_{TOT,IM} = \sqrt{\beta^2_{RC,IM} + \beta^2_{UC,IM}}$$

PEAK STOREY DRIFT DEMAND

$$\beta_{D,\theta} = \sqrt{\beta^2_{DR,\theta} + \beta^2_{DU,\theta}}$$

PEAK FLOOR ACCELERATION DEMAND

$$\beta_{D,a} = \sqrt{\beta^2_{DR,a} + \beta^2_{DU,a}}$$

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TOTAL

RECORD TO RECORD

MODELLING UNCERTAINTY

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TOTAL — RECORD TO RECORD — MODELLING UNCERTAINTY

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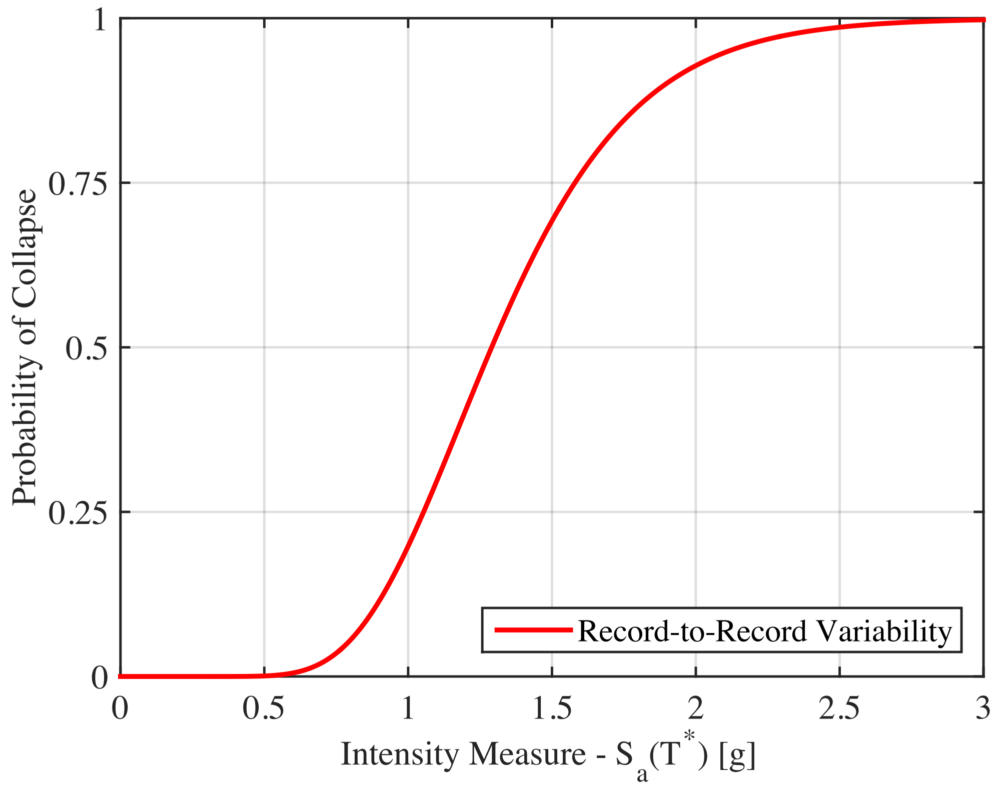
COLLAPSE $$\beta_{TOT,IM} = \sqrt{\beta_{RC,IM}^2 + \beta_{UC,IM}^2}$$ **Look at collapse first**

PEAK STOREY DRIFT DEMAND $$\beta_{D,\theta} = \sqrt{\beta_{DR,\theta}^2 + \beta_{DU,\theta}^2}$$

PEAK FLOOR ACCELERATION DEMAND $$\beta_{D,a} = \sqrt{\beta_{DR,a}^2 + \beta_{DU,a}^2}$$

TOTAL — RECORD TO RECORD — MODELLING UNCERTAINTY

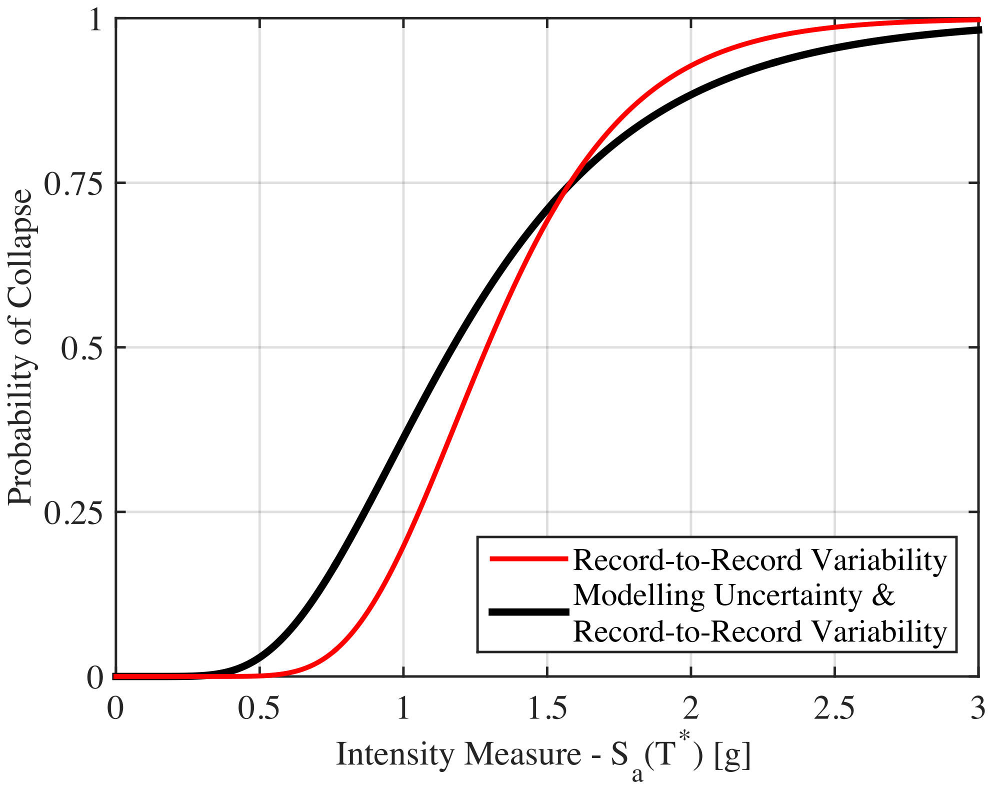
Collapse Fragility



3 storey RC frame w/o infill

- Collapse fragility function developed using the deterministic model with median values and record-to-record variability.

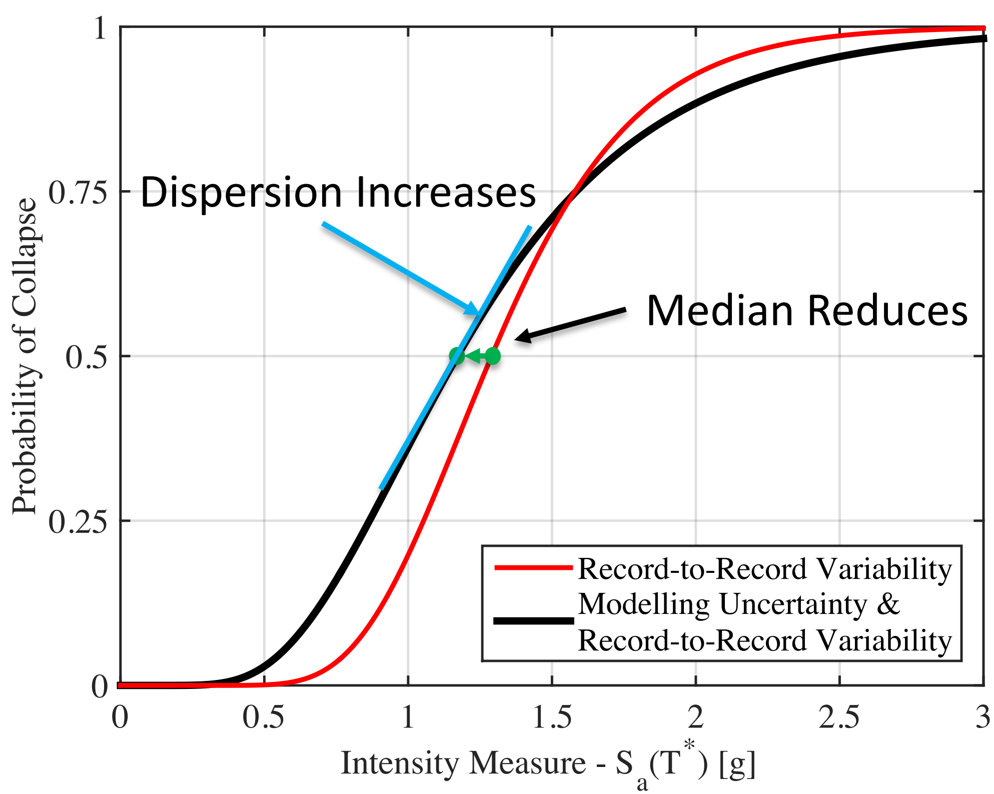
Collapse Fragility



3 storey RC frame w/o infill

- Collapse fragility function developed considering both the record-to-record variability and modelling uncertainty.
- Note that the median has slightly reduced and the dispersion has increased, which is an observation consistent with past studies.

Collapse Fragility



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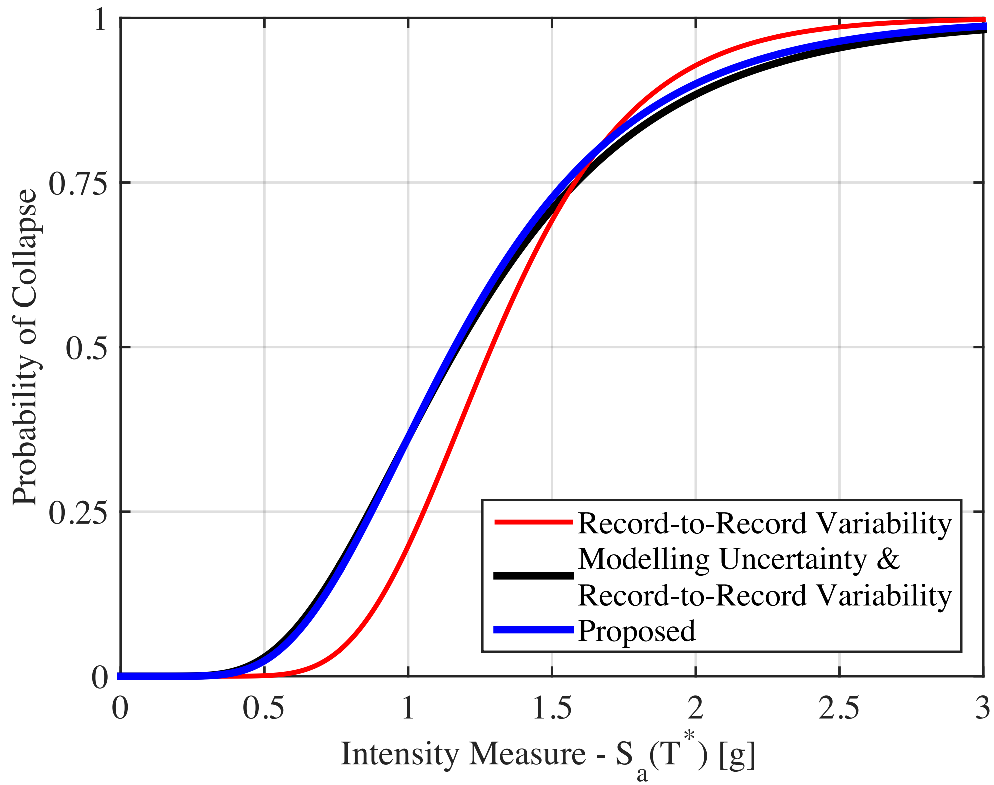

3 storey RC frame w/o infill

- Using the set of median reduction factors (R_c) and modelling uncertainty ($\beta_{UC,IM}$) to be added using an SRSS combination, the proposed modification matches the actual collapse fragility well, especially in the lower tail.

Proposed Dispersion Values for Collapse

- A similar comparison is also carried out for the other frame typologies
- The proposed values for the collapse fragility adjustment to account for modelling uncertainty are shown below.
- These values are separated in terms of the frame typology, which are typical of older GLD RC frames in Italy.

Structural Typology	R_c	β_m
w/o Infill	0.89	0.30
Pilotis Frame	0.95	0.30
Infill Frame	0.99	0.15

Analysis Results

- Incorporating the modelling uncertainty is typically done by inflating the dispersion due to record-to-record variability using as SRSS combination.
- As this study focuses on both the collapse fragility and the demands in the building, we will refer to the following:

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$$\beta_{TOT,IM} = \sqrt{\beta^2_{RC,IM} + \beta^2_{UC,IM}}$$

PEAK STOREY DRIFT DEMAND

$$\beta_{D,\theta} = \sqrt{\beta^2_{DR,\theta} + \beta^2_{DU,\theta}}$$

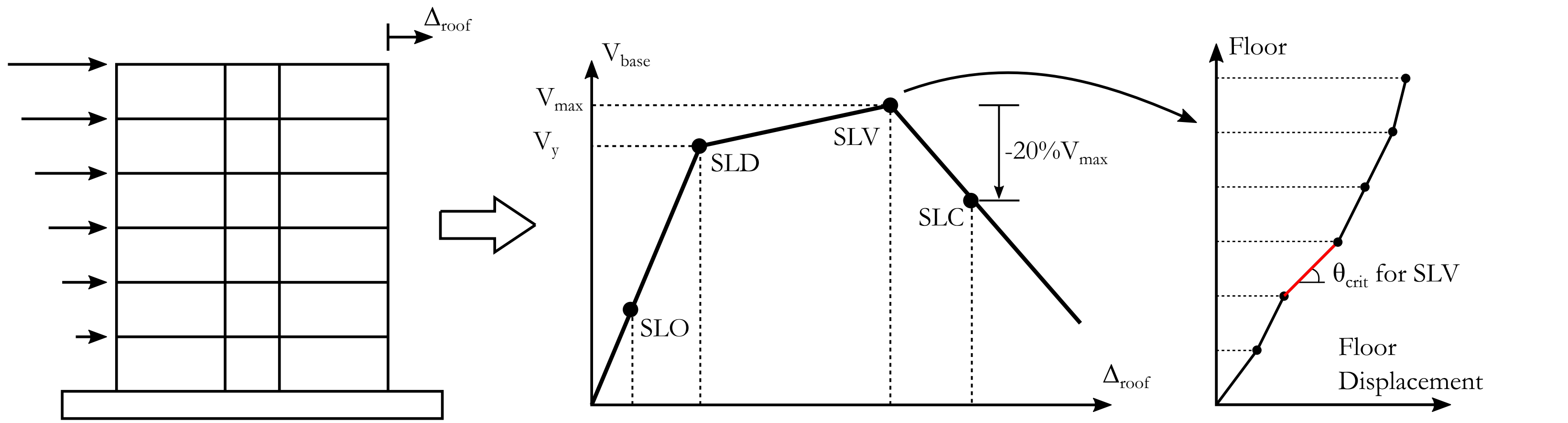
PEAK FLOOR ACCELERATION DEMAND

$$\beta_{D,a} = \sqrt{\beta^2_{DR,a} + \beta^2_{DU,a}}$$

Now look at the influence on the drift and acceleration demand

TOTAL — RECORD TO RECORD — MODELLING UNCERTAINTY

Identification of NTC 2008 Limit States



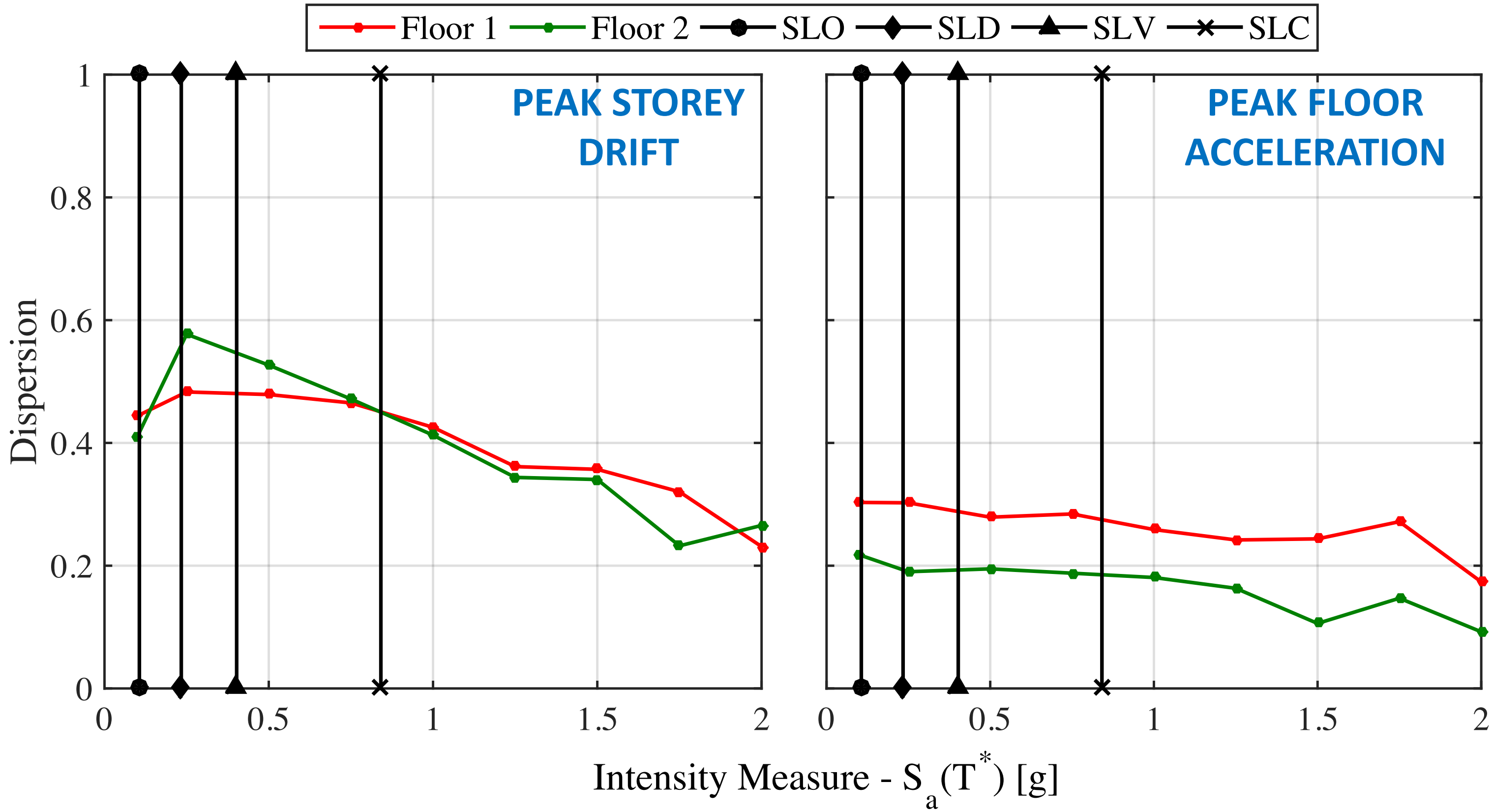
(a) Static Pushover (SPO) **(b) Identification of Limit-States** **(c) Establish Performance Criterion**

- The performance limit states of NTC 2008 were identified.
- These definitions can be later used to refer to the different limit states with respect to ground motion intensity to define overall structural performance.

SLO	Stato Limite di Operatività	Operational
SLD	Stato Limite di Danno	Damage Limitation
SLV	Stato Limite di salvaguadia della Vita	Life Safety
SLC	Stato Limite di prevenzione del Collasso	Collapse Prevention

Demand Parameters

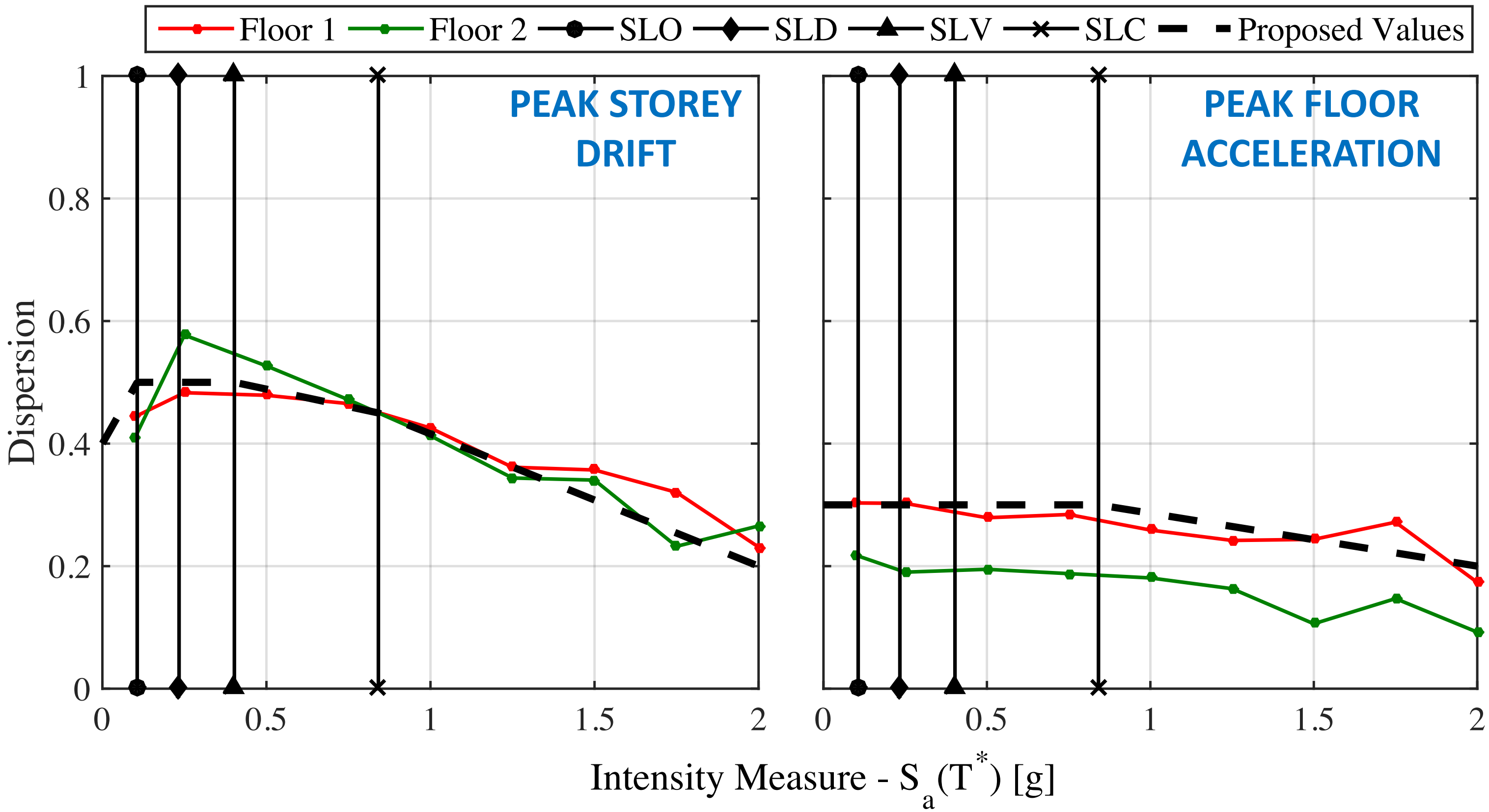
3 storey RC frame w/o infill



- The modelling uncertainty associated with the PSD and PFA demand is illustrated.
- The median values of the four limit states of are also shown to illustrate the change in modelling uncertainty with respect to these limit states.

Demand Parameters

3 storey RC frame w/o infill



- The modelling uncertainty associated with the PSD and PFA demand is illustrated.
- The median values of the four limit states of are also shown to illustrate the change in modelling uncertainty with respect to these limit states.

Proposed Dispersion Values for Demand

- The modelling uncertainty associated with both the PSD and PFA for different limit states has been determined.
- These are separated in terms of the GLD frame typology and also limit state.
- These are especially noteworthy when considering the impacts of masonry infill on dispersion, whereas currently default values available in the literature (e.g. FEMA P58) are not developed with these typologies in mind.

PEAK STOREY DRIFT

Structural Typology	SLO	SLD	SLV	SLC
w/o Infill	0.50	0.50	0.50	0.45
Pilotis Frame	0.50	0.50	0.50	0.40
Infill Frame (Strong)	0.50	0.80	0.90	0.90
Infill Frame (Weak)	0.30	0.50	0.60	0.60

PEAK FLOOR ACCELERATION

Structural Typology	SLO	SLD	SLV	SLC
w/o Infill	0.30	0.30	0.30	0.30
Pilotis Frame	0.25	0.25	0.25	0.25
Infill Frame (Strong)	0.40	0.30	0.30	0.30
Infill Frame (Weak)	0.30	0.30	0.30	0.30

Concluding Remarks

- This paper discussed the quantification of the modelling uncertainty associated with the various demand parameters typically used in the assessment of GLD RC frames Italy.
- In terms of collapse fragility of GLD RC frames with infill:
  - Modelling uncertainty tends to reduce the median collapse intensity and increase the dispersion.
  - Empirical values for the reduction of the median collapse intensity and the increase in the dispersion for the collapse fragility are provided with respect to structural typology.
- In terms of the response of GLD RC frames with infill:
  - Modelling uncertainty was seen to increase the dispersion of the PSD and PFA.
  - Empirical dispersion values to account for modelling uncertainty were proposed as a function of the different limit states, structural typology and the demand parameter of interest.
- Comparing the proposed values with existing empirical values available in the literature (i.e. FEMA P58), the increased dispersion associated with modelling uncertainty was seen to be quantitatively different from other structures such as modern ductile RC frames without masonry infills.
- This highlights how default values provided in guidelines such as FEMA P58 cannot be reasonably adopted.

Thank you for your attention

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