EDPs for damage accumulation in URM buildings and RC columns

Pablo Alfonso Garcia de Quevedo Iñarritu

Nevena Šipčić

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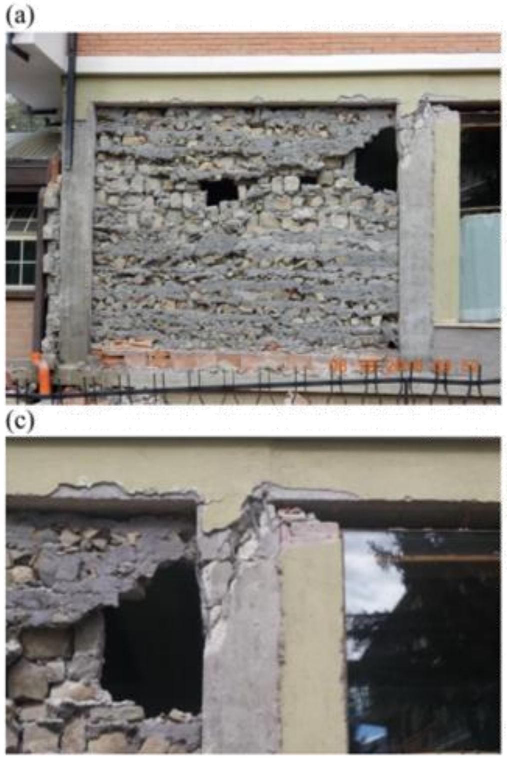
Motivation

- Several seismic sequences proved that already damaged buildings are more vulnerable due to the damage accumulation. However, traditionally, pristine conditions are assumed!

<u>After mainshock</u>



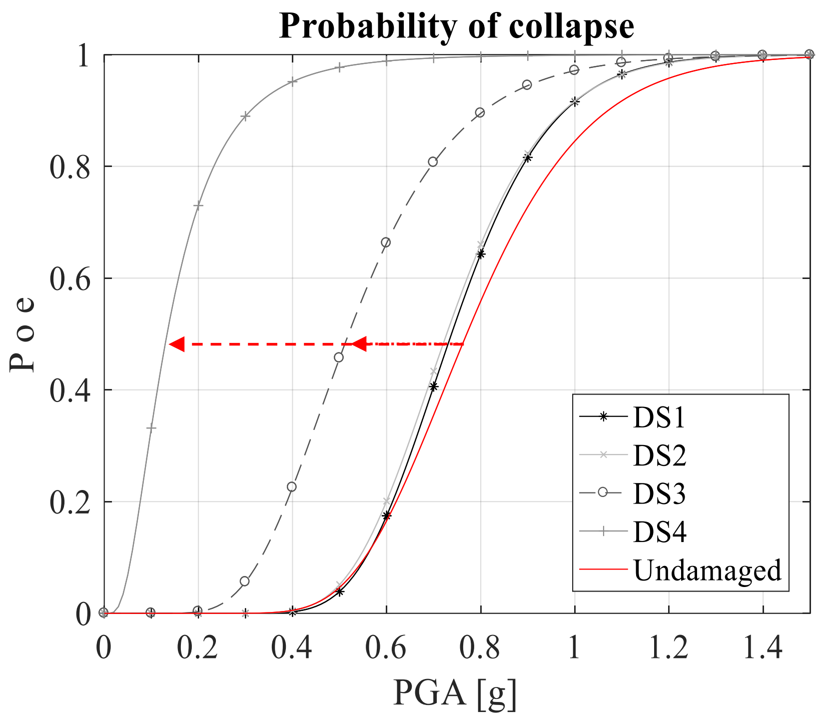
<u>After entire sequence</u>

*RC frames with infills

*Masonry buildings

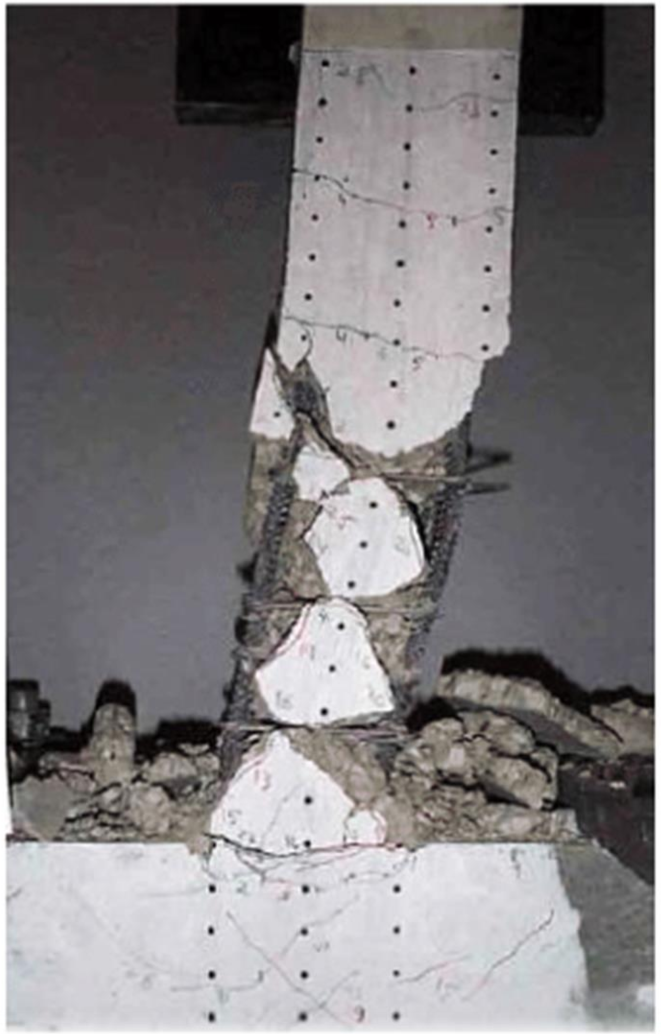
Our objective

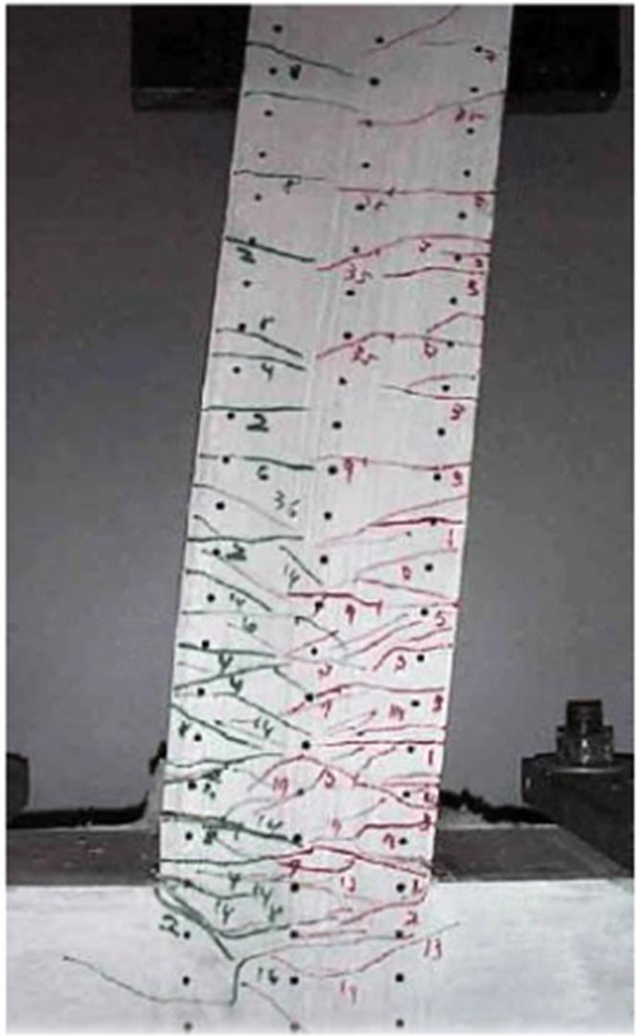
- Investigation of the progression of damage in URM buildings and RC columns
- Calibration of the cumulative EDP that can effectively identify various damage states and serve as a good candidate for the development of damage state dependent fragility curves in the realm of clustered seismicity risk assessment
- The methodology would consider an element based approach, rather than global metrics (MIDR) that proved to be poor predictors of damage during the seismic sequences



Methodology

- Compile a comprehensive database of experimental tests
- Extract relevant information from the collected data
- Propose the Damage Index (DI) capable of capturing damage accumulation
- Calibrate the parameters of the proposed DI using experimental data
- Define distinct damage states for different components
- Validate the effectiveness of the proposed DI through shake-table tests
- Compare the proposed DI with conventional, non-cumulative EDPs such as MIDR

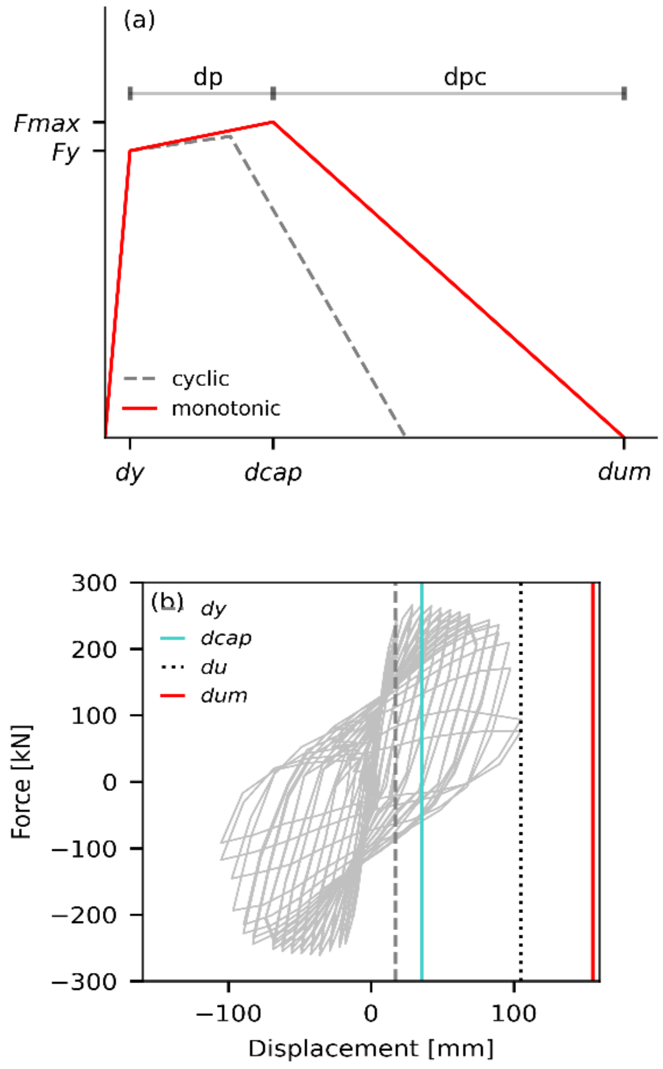




RC columns

Compiling the database of experimental tests

- Two main sources of data:
  - Data gathered by ACI committee 369
  - Database developed for the SERIES research project
- Only rectangular columns are considered
- All specimens are subjected to pseudo-static cyclic loading
- In total there are 370 specimens, 251 that fail in flexural mode (FC), 36 in shear mode (SC) and remaining 83 in flexure-shear mode (FSC).
- Based on the provided information (force-displacement data, material and geometric properties, axial load, etc.) characteristic points are extracted – yield point, capping point, ultimate displacement.
- Keep in mind that this is not a straightforward process!



Proposing the damage index

- Based on the popular Park and Ang damage index that is found as the sum of the deformation and energy terms:

$$\mathrm{DI} = \frac{d_{max} - d_y}{d_{u,m} - d_y} + \beta \frac{E_p}{\gamma\, F_y (d_{u,m} - d_y)}$$

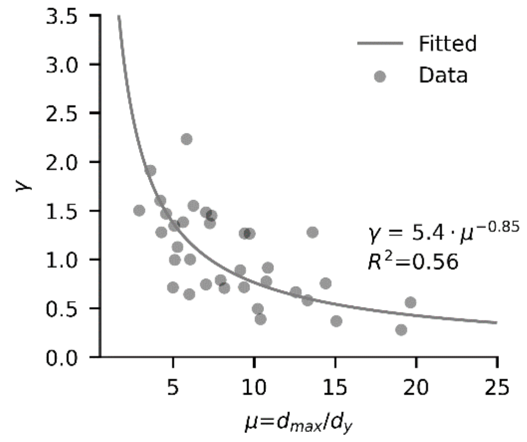
- Parameter γ is added – correlation with number of cycles is found for the case of FC columns…

… and with the ductility for SC columns.

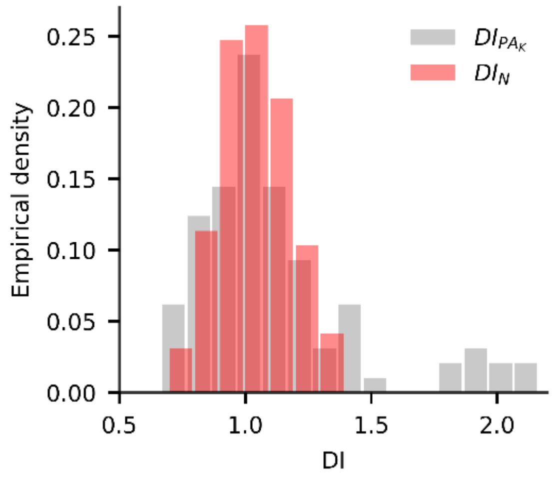
- Std in DI for FS and SC is reduced when parameter γ is added (from 0.32 to 0.1 and from 0.2 to 0.1, respectively).

- No correlation is found for FSC columns – lack of data? DI with γ = 1 and β calibrated with our data is used;

SC columns



FC columns

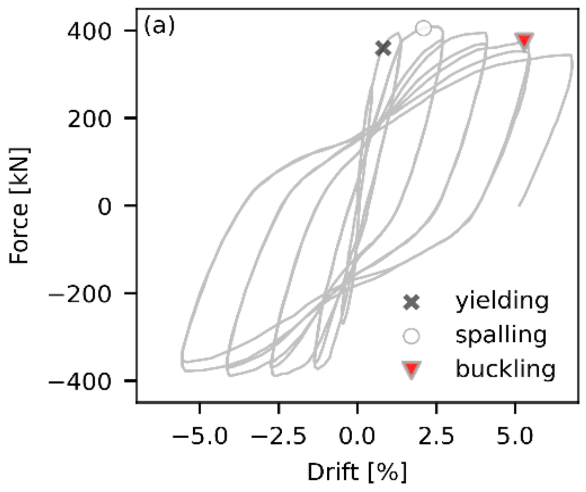


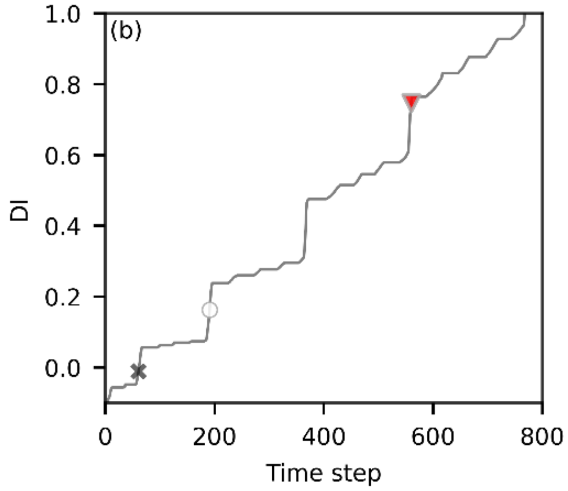
DI values corresponding to different damage states

- Using the experiments where detailed description of damage is provided damage states are proposed

FC	Median value	16th - 84th percentile	Proposed range	Description of damage
DS1	–	–	0 – 0.2	Flexural and longitudinal cracking, yielding of steel bars in tension, followed by shear cracking
DS2	0.17	0.13-0.25	0.2 – 0.4	The onset of concrete spalling exposing the transverse reinforcement
DS3	0.38	0.3-0.50	0.4 – 0.75	More significant spalling of concrete, longitudinal steel is exposed, the potential start of tie yielding
DS4	0.91	0.76-0.98	> 0.75	Major safety implications, bar buckling, concrete core crushing, fracture of the bars, complete failure

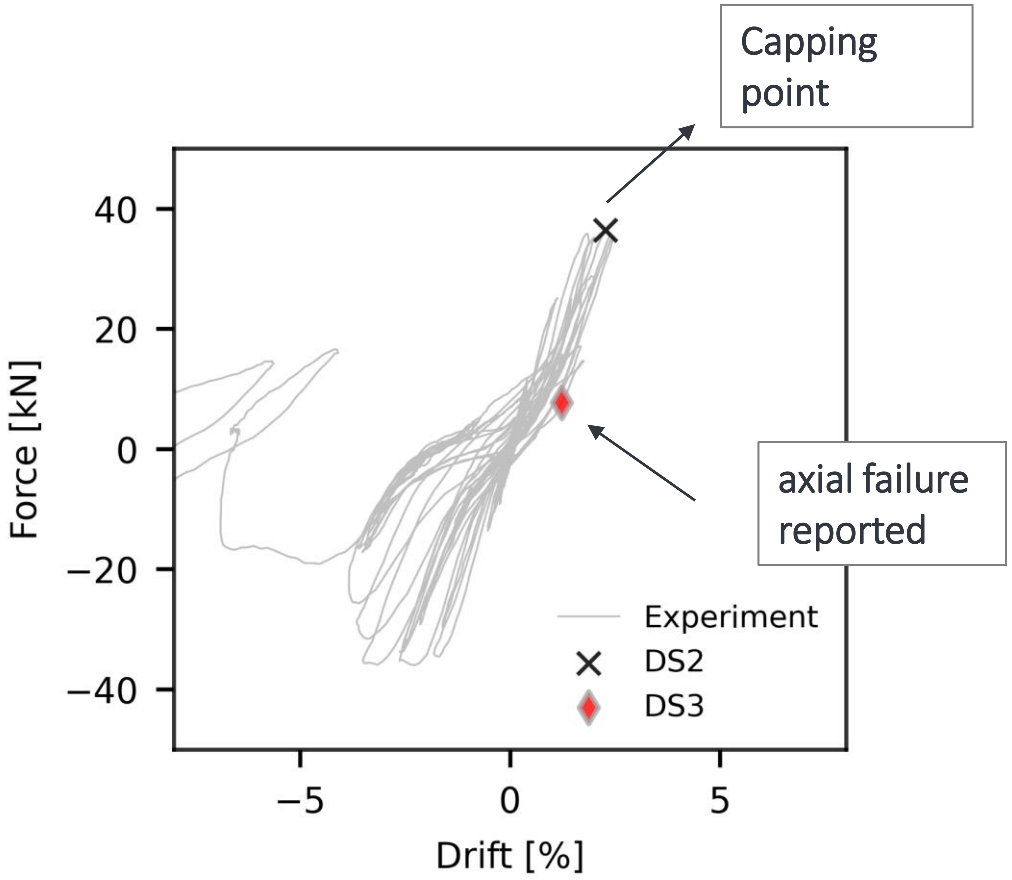
	Median value	16th - 84th percentile	Proposed range	Description of damage
DS1	–	–	0 – 0.25	Flexure-shear cracking, formation of splitting cracks
DS2	0.27	0.15-0.4	0.25 – 0.45	Widening and localization of the shear cracks, onset of concrete spalling;
DS3	0.73	0.45-0.90	>0.45	Longitudinal bar buckling yielding of transverse reinforcement, crushing of the concrete core, axial failure;





Validation with shake-table tests

- Shake-table tests validation is a critical step within the proposed methodology as there is limited amount of data with the detailed description of damage thorough the experiment
- Additionally, we need to know the time step at which certain damage occurred to be able to find the corresponding dissipated energy
- All of the shake table tests that we gathered pertain to the flexure-shear-critical columns (23 tests in total)



- Example – test from Shin (2005)
  - DI2 = 0.35 (0.1+0.25)
  - DI3 = 0.85 (0.3+0.55)

	Median value	16^{th} - 84^{th} percentile	Proposed range
DS1	-	-	0-0.30
DS2	0.33	0.14-0.74	0.30-0.60
DS3	0.9	0.6-1.2	>0.60

Masonry buildings

URM buildings – Methodology

- The proposed way to measure damage on the URM elements is through a modified version of the Park and Ang Damage Index.

$$DI = \frac{\mu_m - \mu_0}{\mu_{u_{mono}} - \mu_0} + \delta \frac{E_H(\mu)}{F_y d_y(\mu_u - 0.5)}, \text{where } \delta = \frac{\beta}{\gamma}$$

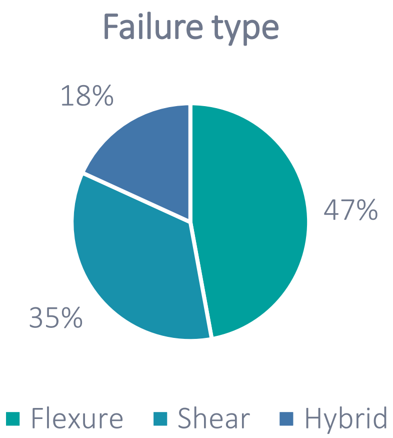
- It considers both deformation and energy term
- It can capture the progression of damage even when IM(AS)<IM(MS).
- It is necessary to calibrate the parameters (β, γ) of the proposed DI through experimental data

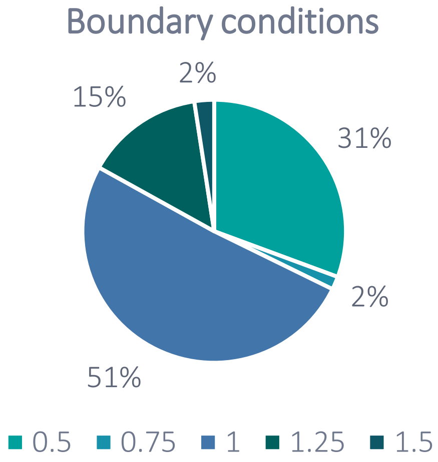
Pier database

- Database for piers consists of around 100 non-linear static tests.
- About 25 detailed data (progression of damage during the test is given).

Detailed damage information during test available	
Crack measurements	9
Photographic/descriptions	6
Sensor	14
Optical sensors	11

*Photos from Petry and Beyer, 2014





EDP calibration for URM piers

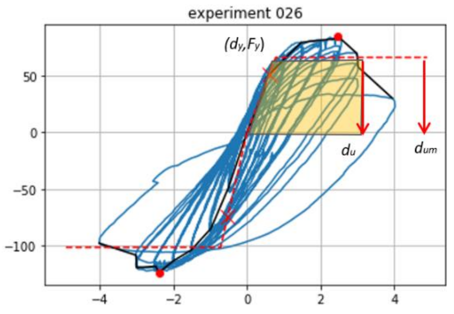
- The DI parameters β and γ are calibrated using all available tests at collapse

$$DI = \frac{\mu_m - \mu_0}{\mu_{u_{mono}} - \mu_0} + \delta \frac{E_H(\mu)}{F_y d_y(\mu_u - 0.5)} = 1 \quad \text{at collapse}$$

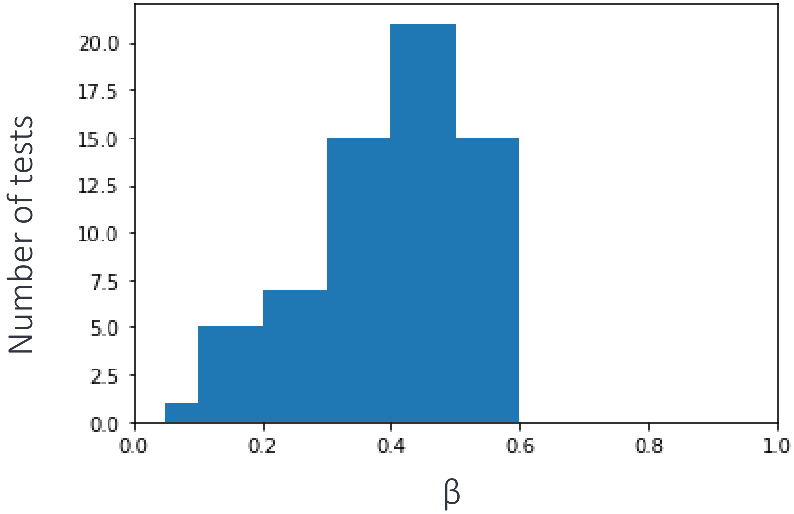
$$\gamma = \frac{E_H}{E_{Mono}}$$

- Using the hysteretic energy and drifts from tests at collapse.

*Photo from Petry and Beyer, 2014



For all tests



EDP calibration for URM piers

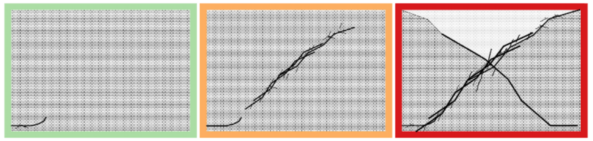
- Detailed tests are used to estimate the DI ranges (0-1) at which each different physical DS (EMS-98 or FEMA based) are achieved.
- Depends on the failure mode, as descriptions and conditions change.

Shear/Hybrid:

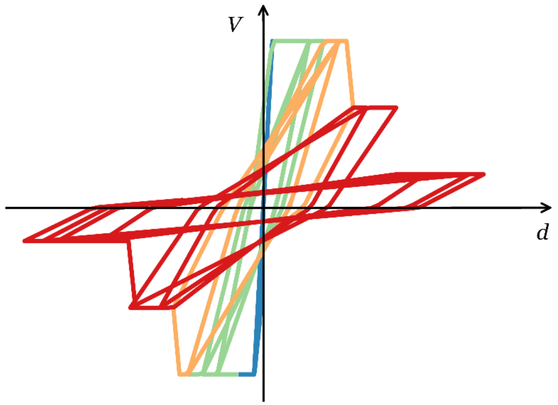
DS	16th-84th range	5th-95th range	Proposed range
1	0.023 - 0.045	0.015 - 0.0525	0.025-0.05
2	0.05 - 0.12	0.0275 - 0.14	0.05-0.125
3	0.19 - 0.41	0.12 - 0.49	0.125 - 0.45
4	0.52 - 0.7	0.47 - 0.77	0.45 - 0.7
5	0.67 - 0.98	0.58 - 1.1	> 0.7

Flexure:

DS	16th-84th range	5th-95th range	Proposed range
1	0.018 - 0.0425	0.0075 - 0.0525	0.02 - 0.075
2	0.12 - 0.17	0.11 - 0.18	0.075 - 0.20
3/4	0.32 - 0.6	0.24 - 0.7	0.2 - 0.70
5	1 - 0.85	0.5 - 0.94	> 0.70

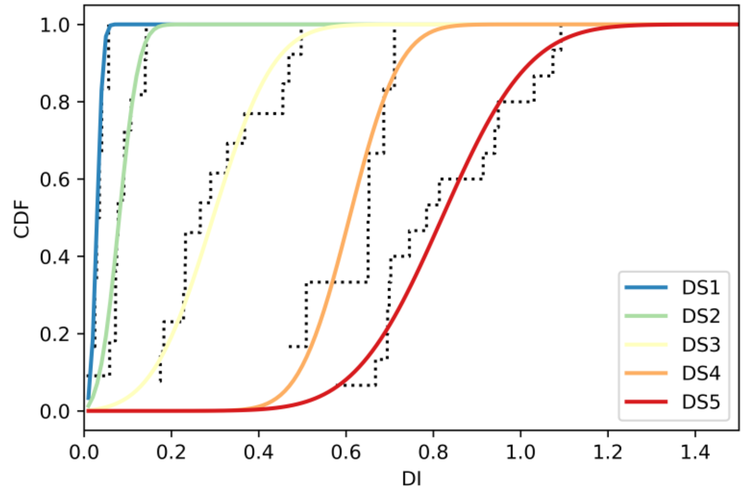


Observed DS (fits description)



Compute DI value at each point.

Shear/Hybrid:



EDP calibration for URM spandrels

- Database of 19 tests. Not many available in literature
  - Using the available data, tests by Beyer, Graziotti, Gattesco and Parisi.
- Calibration of the DI parameters through experimental tests like the piers.
- Similar values to those obtained by the piers, slightly higher energy contribution.
- Using the detailed data on cracks + hysteretic response, and EMS-98 DS to compute the DI thresholds.
- No distinction between failure mode, as there isn't enough data

DS	16th-84th range	5th-95th range	Proposed range
1	0.018 - 0.045	0.01 - 0.055	0.02 - 0.05
2	0.0675 - 0.19	0.0325 - 0.23	0.05 - 0.2
3/4	0.19 - 0.51	0.095 - 0.62	0.2 - 0.60
5	0 - 0.82	0.26 - 0.97	> 0.60

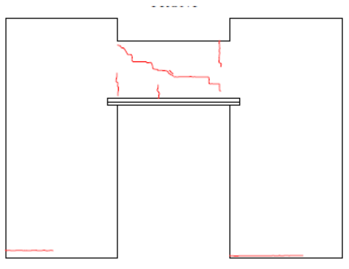
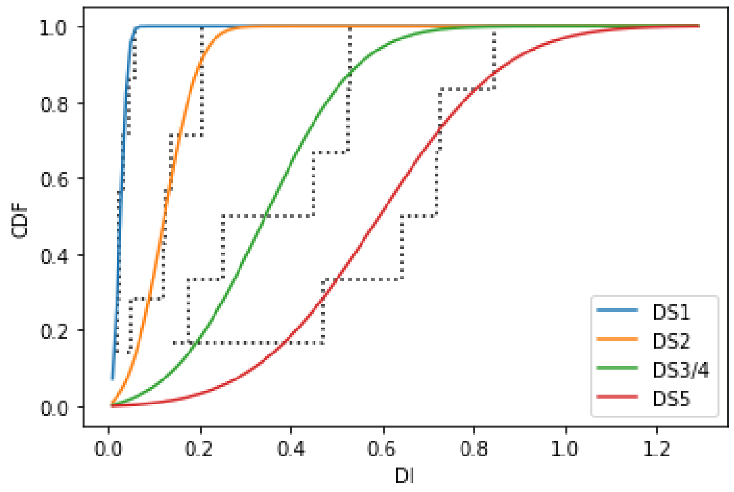


*Figure from Parisi et al, 2014

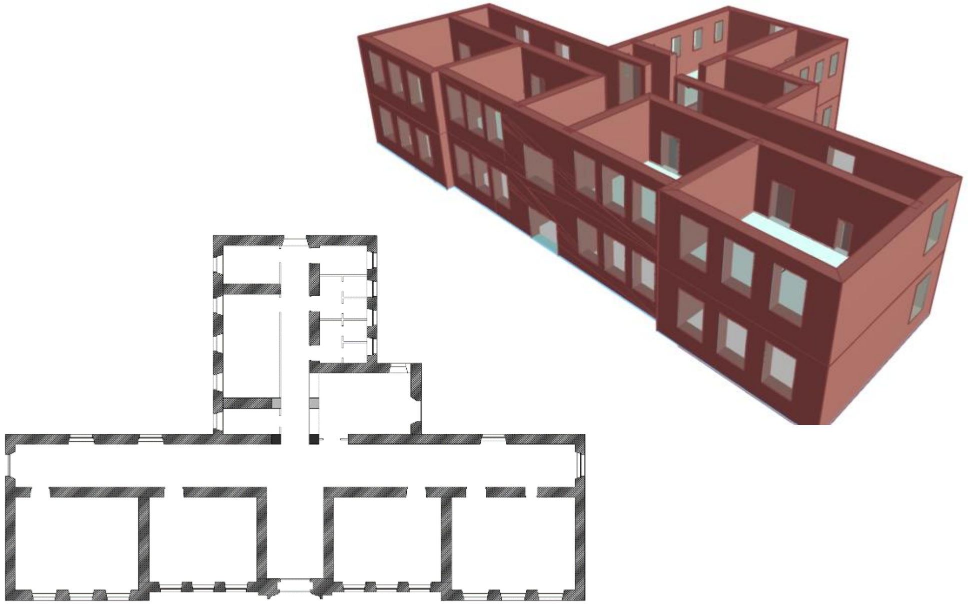
Tεks)

n	Spandrels ($DL_{S,k}$) (Fig. 5c)
0	No cracks
1	Low crack-band at the end elements
2	Larger cracks at the end elements or occurrence of shear failure in the central part of the element (achievement of the strength for that portion of the masonry) or diagonal crack that occurred at the center of the panel (achievement of the maximum strength)
3	Significative degradation phase that occurred for the masonry portion; the residual resistance is related to the lintel capacity
4	
5	Lintel collapse

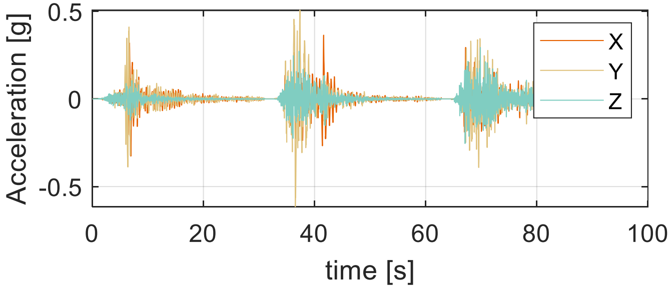


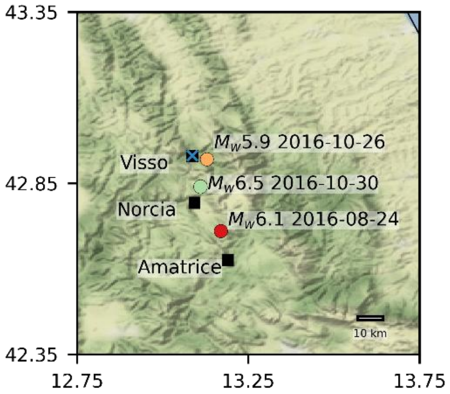
Validation: available data

- Attempted on shake table tests but most exhibit flexural failure on elements, and have incremental levels of shaking.
- Building model of Visso School, damaged during the 2016 Central Italy sequence.
    - We know the ground motions at the site (instrumented).
    - There is survey information about the damage after each event. Progressively more damaged.
    - We have the Equivalent Frame model (Tremuri software).



*Photos from Brunelli et al, 2021

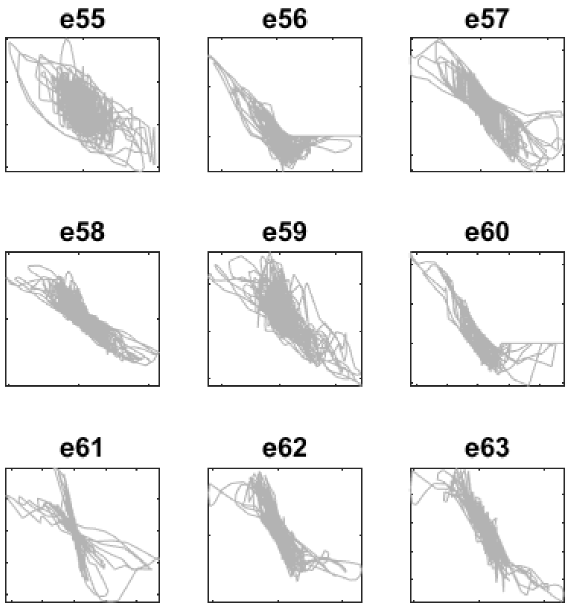




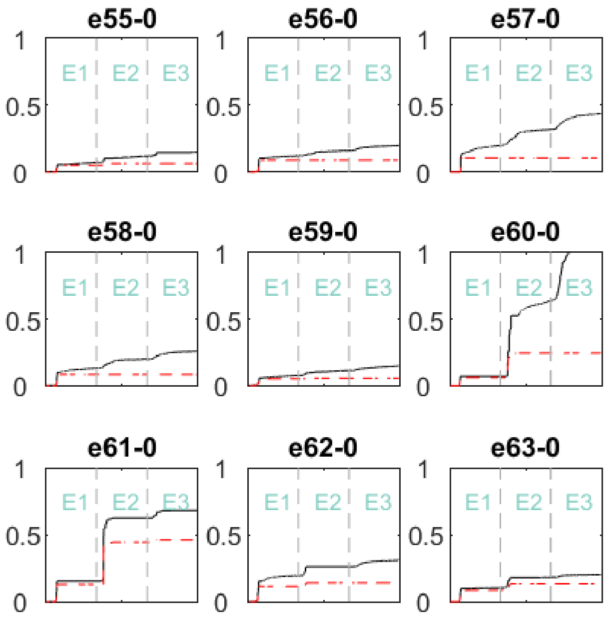
Validation: procedure

- The damage on each element is evaluated computing the DI after each event using the response.
- Using the thresholds of DI we can identify a damage state for each member.
- Damage is combined per wall and compared to the observed damage.

Hysteretic behavior:



Computed DI:



Observed damage:

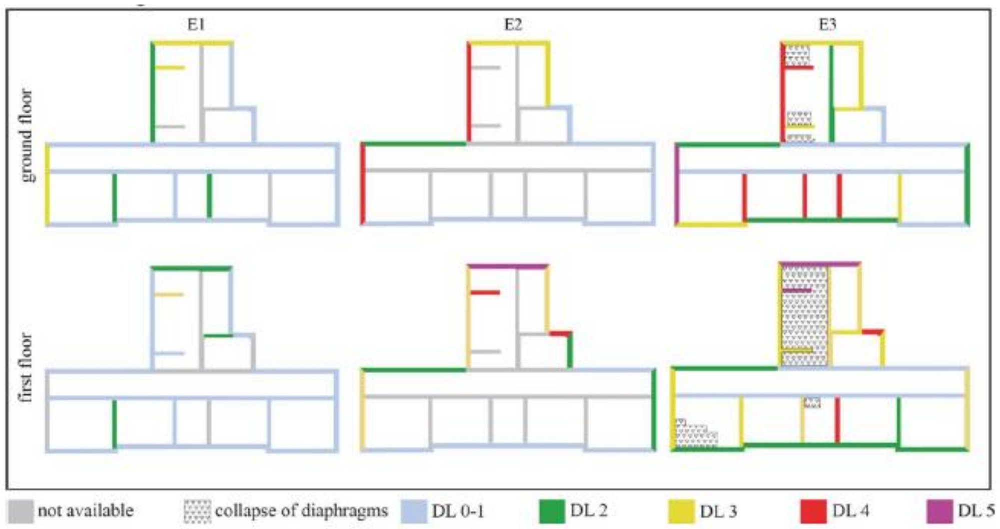
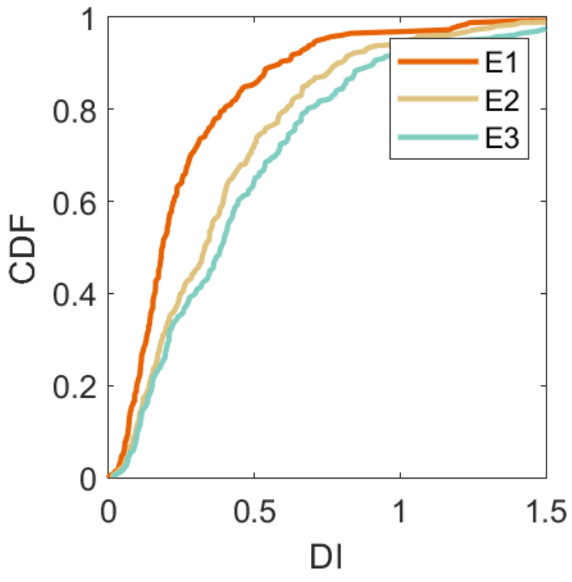


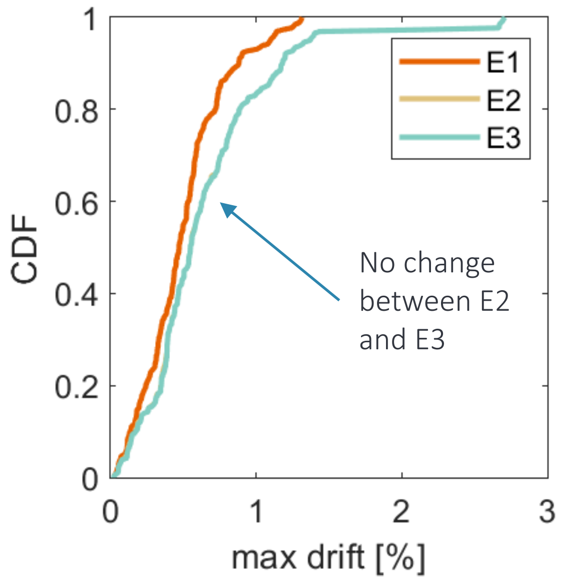
*Figure from Brunelli et al 2021

Validation: outputs

- We see an increase of damage on the elements after each shock, drift-based/global metrics cannot capture this.
- Tends to overestimate slightly, however there is some uncertainty in the observations for the first 2 shocks (only photos) and improvements are still possible.

Per element:





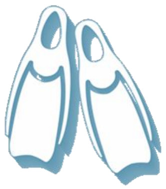
	Observed						Simulated					
	X			Y			X			Y		
	E1	**E2**	**E3**	**E1**	**E2**	**E3**	**E1**	**E2**	**E3**	**E1**	**E2**	**E3**
DLG	2	3	3	2	**3**	**4**	3	4	4	3	**3**	**4**

Global metrics:

Max RDR [%]	**X**	**Y**
E1	0.358	0.446
E2	0.387	0.673
E3	0.288	0.255

Conclusions

- Cumulative EDPs are essential for assessing the damage within the clustered seismicity framework
- We investigated damage progression in RC columns and URM piers and spandrels
- Damage indices based on Park and Ang DI are proposed and calibrated based on the experimental data
- Preliminary results suggest that the proposed DI for URM shows an increase of damage on the elements after each shock while drift-based metrics cannot capture this
- It is crucial to validate our findings with additional shake-table tests and real buildings!



Contact:
nevena.sipcic@iusspavia.it
pablo.garcia@iusspavia.it